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U.S. ARMY
MATERIEL COMMAND

— COMMITTED TO PROTECTION OF THE ENVIRONMENT —

Groundwater Monitoring Program
Final Annual Groundwater Monitoring Report for 1991

Volume I of II

September 18, 1992
Contract No. DAAA15-88-D-0021
Delivery Order 0006

Harding Lawson Associates

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PREPARED BY

Harding Lawson Associates

PREPARED FOR

PROGRAM MANAGER FOR ROCKY MOUNTAIN ARSENAL

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EXECUTIVE SUMMARY

The groundwater element of the Comprehensive Monitoring Program (CMP) at the Rocky Mountain Arsenal (RMA), Commerce City, Colorado, was designed to provide continual and long-term monitoring of groundwater at RMA and adjacent offpost areas to the north and northwest. Groundwater data were collected during the 1991 water monitoring year to (1) assess changes in th. ate and extent of contaminant migration, (2) monitor the effects of remedial actions, and (3) maintain a database to meet regulatory requirements and support remedial investigation/feasibility study (RI/FS) verification. The 1991 water monitoring year is the first year of implementation of the reduced biennial sampling network described in the CMP Draft Final Technical Plan Addendum (Stollar and others, 1990b).

DESIGN OF THE 1991 WATER MONITORING YEAR PROGRAM

Information for the groundwater element of the CMP is obtained by measuring water levels and collecting and analyzing groundwater samples to assess water quality. Water-level measurements provide information about groundwater flow, and groundwater samples are analyzed to provide information about contaminant distribution. Water levels are measured and groundwater samples are collected from networks of wells that monitor both the shallow unconfined flow system, which includes alluvial and unconfined Denver Formation wells, and the deeper confined flow system that consists of confined Denver Formation wells.

The well network used to measure water levels consisted of approximately 1200 wells; the water level in each well was measured three times during the year. The well network from which groundwater samples were collected consisted of 273 wells during Winter 1990/91, 61 wells during Spring 1991, and 58 wells during Fall 1991. The groundwater samples collected during Winter 1990/91 were analyzed to assess contaminant distribution around four project areas: the North Boundary Containment/Treatment System (NBS), the Northwest Boundary Containment/Treatment System (NWBS), the Basin F Interim Response Action (IRA) area, and the

Basin A Neck Groundwater Intercept and Treatment System. The groundwater samples collected during Spring and Fall 1991 provided two additional rounds of data for the Basin F IRA area.

Fewer CMP wells were sampled during the 1991 water monitoring year than during previous years because analytical results from the 1988 and 1989 CMP indicated that regional contaminant distribution patterns did not change significantly in areas unaffected by current IRA and boundary system cleanup efforts. In September 1990, a proposed modification to the CMP groundwater monitoring program was prepared (Stollar, 1990a) detailing the new program direction, which would optimize network efficiencies and maximize data utility. During the 1991 water monitoring year, the following program modifications were made:

- Samples were not collected from the annual well network.
- Three instead of four sampling events were conducted.
- The semiannual sampling round was converted to the benchmark round sampled in Winter 1990/91. (The benchmark round was scheduled to be sampled in Fall 1990 but because of delays in finalizing the sampling plans, it was conducted in Winter 1990/91. The benchmark network is a subset of the biennial network that provides annual data for the purpose of assessing long-term contaminant concentration trends in response to contamination cleanup.)
- The Basin F IRA area network was sampled twice, once in Spring 1991 and once in Fall 1991.

The groundwater samples collected during the 1991 water monitoring year were routinely analyzed for 59 target analytes, including both organic compounds and inorganic constituents. In addition, approximately 20 percent of groundwater samples collected during Spring 1991 were analyzed by gas chromatography/mass spectrometry (GC/MS) methods to confirm or reject the presence and extent of organic compounds detected by GC techniques and to identify any compounds not among the 59 target analytes that were regularly detected. The target analytes for the 1991 water monitoring year were the same as those for the 1990 water monitoring year. Similar to the 1990 program, the analytical program for the 1991 water monitoring year also incorporated a quality assurance/quality control (QA/QC) program designed to produce accurate, defensible, and reproducible analytical results.

RESULTS OF THE 1991 WATER MONITORING YEAR PROGRAM

Water-level data obtained during the 1991 water monitoring year were used to assess groundwater flow in both the unconfined and confined flow systems at RMA. The regional direction of groundwater flow is from southeast to northwest.

Although unconfined groundwater flows generally to the northwest, local variations in this regional pattern are observed. These variations often occur where groundwater flows from higher hydraulic conductivity alluvial sediments to lower hydraulic conductivity Denver Formation bedrock. For instance, flow near the edges of unsaturated alluvium areas often varies from the regional pattern. The most pronounced variation from the regional water-table pattern at RMA occurs in the South Plants area where a mound approximately 20 to 30 feet higher than the surrounding regional water table exists. Seasonal fluctuations in the regional water table during the 1991 water monitoring year were small. The largest water-level fluctuation not associated with boundary system operations was approximately 7 feet and occurred in the South Plants area during Spring 1991. In addition, municipal pumping of South Adams County wells in onpost Section 33 caused water-level fluctuations of approximately 7 to 15 feet. However, general configuration of the regional water-table surface remained consistent throughout the 1991 water monitoring year. This consistency indicates that regional groundwater flow patterns also remained consistent. The South Platte River, which is approximately 2 miles northwest of the RMA boundary, acts as a major discharge area for the regional unconfined flow system.

The potentiometric surfaces of the confined flow system are generally lower in elevation than the potentiometric surface of the overlying unconfined flow system. The potentiometric surfaces of separate zones within the confined system generally decrease with depth. This indicates that there is a potential for downward flow between the unconfined and confined flow system and between different zones within the confined flow system. Local variability in hydraulic conductivity and the degree of hydraulic interconnection between stratigraphic intervals may result in local variations in flow direction. Evidence of localized variations in flow direction included upward vertical gradients between the confined and unconfined flow system, which were identified by well cluster data. Seasonal water-level variations measured in the confined flow system were less than seasonal variations measured in the unconfined flow system.

Water-level data for the vicinity of the containment systems were examined in greater detail. Water-table fluctuations at the NBS were less than 8 feet among the three sampling rounds. Some of the water-level fluctuations reflect changes in the operations of the boundary system to establish a reversal in hydraulic gradient across the NBS to oppose the regional gradient. Cross sections of the water table indicate the western portions of the NBS displayed a reversed hydraulic gradient for the entire 1991 water monitoring year. Although the eastern portion of the NBS did not display a reversed hydraulic gradient, the magnitude of the hydraulic gradient decreased during the 1991 water monitoring year.

Data from a limited number of wells in the confined Denver Formation indicate that a lateral reversed hydraulic gradient was not established at the NBS throughout most of the 1991 water monitoring year. However, data collected during September 1991 indicate that seven confined Denver Formation wells upgradient along the western end of the NBS exhibited upward vertical gradients and therefore reduced the possibility for migration of contaminated ground-water under the NBS during the time these data were collected. Evaluation of the variability in the vertical gradient at the NBS caused by operational changes was not possible because of insufficient data.

Water-table fluctuations at the NWBS were less than 8 feet among the three sampling rounds. The extent of the NWBS that experienced a reversed hydraulic gradient remained approximately the same throughout the 1991 water monitoring year. The reversal in hydraulic gradient was most successful along the original portion of the barrier wall. During the 1991 water monitoring year, a reversal in hydraulic gradient was not established along the northeastern portion of the wall where the extension was added during 1990, but the southwestern (hydraulic barrier) portion of the NWBS did maintain a reverse gradient throughout the 1991 water monitoring year.

Analytical data obtained during the 1991 water monitoring year were used to assess contaminant distribution. Analytical results for the 1991 water monitoring year were presented on plume maps for the 1990 water monitoring year for five compounds detected in samples from wells in the unconfined flow system. Analytical results were not contoured to create new plume maps because of the lack of sufficient data. The regional configuration of most plumes remained similar to the configuration mapped in the 1990 water monitoring year.

Slight differences in data between the 1990 and 1991 water monitoring years often reflected the addition of new wells. Areas where contamination was identified in the confined flow system were generally beneath areas previously identified as contaminated in the unconfined flow system, which indicates possible vertical migration of contaminants. Contaminant distribution in the confined flow system is generally at lower concentrations and less areally extensive than in the unconfined flow system.

Analytical data indicate that operation of the NBS and recharge trenches has decreased contaminant concentrations north of the NBS. However, the decreases in concentration are relatively insignificant in areas other than near the recharge trenches. The decreased contaminant concentrations around the recharge trenches are possibly a result of dilution due to increased recharge rates. The limited number of wells in the confined Denver Formation preclude a definitive interpretation of contaminant distribution in the vicinity of the NBS.

Analytical data indicate operation of the NWBS has resulted in decreasing contaminant concentrations in the offpost area downgradient of the NWBS. In general, the contaminant concentrations detected in samples from wells downgradient of the NWBS are comparable with contaminant concentrations that are reported for the effluent (treated) groundwater at the NWBS.

Several compounds not included on the CMP list of target analytes were detected in samples submitted for GC/MS analysis. The compound 1-chloro-4-(methylsulfanyl)benzene was the most commonly detected compound not on the target analyte list. Other compounds identified by GC/MS analysis, but not on the target analyte list, include organic compounds chemically associated with the organosulfur target analytes. Compounds not on the target analyte list were generally detected in samples that contained elevated concentrations of target analytes.

QA/QC samples were collected and analyzed during the 1991 water monitoring year to evaluate the reproducibility and accuracy of water quality data. These samples consisted of trip, field, and rinse blanks as wells as duplicate samples. Results of the rinse blanks indicated that decontamination procedures may not have been sufficient at some highly contaminated wells. Analytical results of the duplicate samples revealed that volatile organic analyses deviated on average by a factor of 1.1 from the respective investigative sample, and semivolatile and trace inorganic analyses deviated on average by a factor of 1.2 from the respective investigative sample.

CONCLUSIONS

The groundwater data collected as part of the CMP during the 1991 water monitoring year were useful in describing the distributions of groundwater contaminants in IRA areas, specifically the NBS and NWBS. Important conclusions obtained on the basis of data collected during the 1991 water monitoring year are listed below:

1. Regional groundwater flow conditions have not changed significantly since 1987.

2. The use of a smaller well network during the 1991 water monitoring year limited the assessment for the Basin A Neck Groundwater Intercept and Treatment System (BANS) and the Irondale Containment/Treatment System (ICS) but was adequate for assessing the NWBS, NBS, and the Basin F areas.

3. Relative percent difference (RPD) values, which are a measure of the variability between the original and duplicate sample analyses, are considered acceptable, averaging 6.5 percent for volatile analyses, 18 percent for semivolatile analyses, and 16 percent for inorganic analyses. These values are considered acceptable as compared to the average RPD values published by EPA in its guidance on the Development of Data Quality Objectives (EPA, 1987). Published EPA values for acceptable precision for methods similar to those used during the CMP range from 2.8 to 35.5 percent for volatile analyses, 1.8 to 28.1 percent for semivolatile analyses, and 0.3 to 31 percent for inorganic analyses.

4. The potential for contaminant migration beneath the NBS has been reduced but not eliminated as the result of the reverse gradient being established over more of the wall. However, variability in the gradient caused by operational changes could increase the potential for contaminant migration.

5. Increased frequency of hydrologic monitoring upgradient and downgradient of the NBS has provided data to improve the description of gradient reversal along the NBS barrier wall.

6. The extension of the NWBS to the northeast has reduced the potential for contaminant migration offpost.

7. An accurate assessment of contaminant concentrations in areas downgradient (offpost) of the NWBS was not possible with the limited data collected in this area during the 1991 water monitoring ye... The benchmark network that is to be sampled every other year provides enough coverage to assess current IRA areas, with the exception noted above.

1.0 INTRODUCTION

This Draft Annual Groundwater Monitoring Report has been prepared by Harding Lawson Associates (HLA) for the Program Manager for Rocky Mountain Arsenal (PMRMA) as a work requirement under Delivery Order 0006, the Groundwater Monitoring Program (GMP), of Contract No. DAAA15-88-D-0021 between HLA and the U.S. Department of the Army (Army), for services being provided at the Rocky Mountain Arsenal (RMA) in Commerce City, Colorado. This report was prepared using groundwater monitoring data collected by another contractor under the Comprehensive Monitoring Program (CMP) during the 1991 water monitoring year. The 1991 water monitoring year lasted from October 1, 1990, through September 30, 1991.

Section 1.0 of this report provides an overview of site background and discusses the nature and extent of contamination at RMA. This section also summarizes historical groundwater monitoring programs at RMA and indicates how these programs relate to the current CMP. Section 2.0 provides an overview of the geology and hydrology at RMA. The overall CMP strategy, including the well networks designed to monitor water levels and water quality, is described in Section 3.0, where the analytical program and the quality assurance and quality control (QA/QC) program are also discussed. Section 4.0 presents the regional results of the 1991 water monitoring year. A detailed discussion of the results of the 1991 water monitoring year by IRA areas is presented in Section 5.0. Terms used in this report and references used in preparing this report are listed in Sections 6.0 and 7.0, respectively.

1.1 SITE BACKGROUND

RMA occupies approximately 27 square miles in southern Adams County, Colorado, approximately 9 miles northeast of downtown Denver (Figure 1.1). RMA was established by the Army in 1942 to produce chemical and incendiary munitions for World War II. Following World War II, the production of munitions decreased, and the Army leased selected portions of RMA to private industry. A chronological summary of activities at RMA follows.

From 1942 until 1957, chemical agents were manufactured at RMA. Levinstein mustard (H) was produced in the South Plants manufacturing area from 1942 until 1950. This area was also used to fill shells with the chemical agent phosgene or incendiary mixtures, including napalm and white phosphorous. During this period, obsolete World War II munitions were destroyed by detonation or incineration on RMA. The chemical nerve agent isopropylmethyl fluorophosphonate (Sarin or GB) was produced in the North Plants manufacturing area from 1953 until 1957. Munitions filling with this nerve agent continued at RMA until 1969. From 1970 to 1984, Army activities focused primarily on the demilitarization of chemical warfare materials.

In 1947, portions of RMA were leased to private industry. Early lessees included Colorado Fuel and Iron Corporation (CF&I) and Julius Hyman and Company (Hyman). CF&I produced chlorine and chlorinated benzenes and attempted to manufacture dichlorodiphenyltrichloroethane (DDT). Hyman produced several pesticides during this period. In 1950, Hyman added to its lease a number of facilities formerly operated by CF&I. In 1952, Shell Oil Company (Shell) acquired Hyman and operated it as a wholly owned subsidiary until 1954, when Hyman was integrated into the Shell corporate structure and Shell succeeded Hyman as the named lessee. From 1952 until 1982, Hyman and/or Shell produced a variety of herbicides and pesticides in the South Plants manufacturing complex.

Between 1942 and 1982, a variety of the contaminants associated with the industrial activities onsite were released to the environment at RMA. Chemical waste effluents were discharged into lined and unlined evaporation basins, and solid wastes were buried or disposed on the surface. Wastewater, raw materials, and end products were leaked and accidentally spilled within the manufacturing complexes, storage areas, and transportation routes on RMA. Chemical products that were not manufactured to specification were commonly discharged into shallow trenches. Munitions were demilitarized and disposed in trenches and on the surface. The sites that are believed to have been the primary groundwater contamination source areas at RMA are the manufacturing complexes, the wastewater storage and evaporation basins (Basins A, C, D, E, and F), areas of solid waste disposal, and the rail classification yard (Figure 1.2).

In the early 1950s, the detrimental effects of chemical contamination on the local environment became evident. By 1951, high waterfowl mortality was suspected of being linked to the insecticide contamination of three artificial lakes on RMA (Armitage, 1951; Goodall, 1951). In 1954 and 1955, severe crop loss was reported by farmers northwest of RMA using well water for irrigation (U.S. Department of Health, Education, and Welfare, 1965). Two contaminants, diisopropylmethylphosphonate (DIMP), a manufacturing byproduct of the nerve agent GB, and dicyclopentadiene (DCPD), a chemical used to produce insecticides, were detected in offpost surface water in 1974 (R. L. Stollar and Associates, Inc. [Stollar], and others, 1991). Groundwater contaminated with dibromochloropropane (DBCP) and other compounds has been detected in samples from offpost since 1978 (Environmental Science and Engineering [ESE], 1987).

1.2 NATURE AND EXTENT OF CONTAMINATION

Releases of a variety of contaminants to the environment at RMA have resulted in contamination of environmental media both onpost and offpost (ESE and others, 1988; HLA and ESE, 1992; Ebasco Services, Inc. [Ebasco], and others, 1991). This report discusses the impact of such contamination on the medium of groundwater in the RMA area.

The distance that a groundwater contaminant plume extends from its source area depends on numerous factors, including the contaminants' behavior in the environment, the amount and time of the release, and other factors, as noted below. Groundwater contaminant plumes at RMA may extend only a few hundred feet from their sources or may extend miles, as is the case for DIMP. Generally, the occurrence and migration of contaminants in groundwater at RMA is complicated by the following factors:

- Many contaminant sources, some areally separated, some overlapping
- A variety of release scenarios, including single or repeated spills, continuous or intermittent leaks, discharges to ditches or basins, leaching from trenches, and leaching from or direct contact of groundwater with buried transport lines
- Many contaminants
- Spatial variabilities in aquifer properties

- Complex interactions between water-bearing zones
- Historical changes in the distribution and quantity of groundwater recharge

1.3 SUMMARY OF PREVIOUS GROUNDWATER MONITORING

The RMA Contamination Control Program was established in 1974 to ensure compliance with state and federal environmental laws. After the detection of contaminants in samples collected offsite, the State of Colorado issued three administrative orders in 1975 for RMA to cease and desist in activities that could result in contamination of the environment. In response to the cease and desist orders, the Army initiated regional surface-water and groundwater monitoring programs to assess contamination both onpost and offpost. The efforts were carried out under the direction of the RMA Contamination Control Program with objectives being to evaluate the nature and extent of contamination and to develop a means to control contaminant migration.

The Army established the 360 Degree Monitoring Program to monitor groundwater and surface water both on RMA and offpost. The program changed in scope several times from its inception in 1975 to its completion in 1984 in response to the geologic, hydrologic, and chemical information obtained and changing groundwater contamination patterns. During this period, the Army performed numerous other contaminant monitoring tasks and initiated groundwater remediation efforts on RMA. Three boundary containment systems, shown in Figure 1.2, were constructed to intercept and remove contaminants from groundwater and recharge the treated water. The North Boundary Containment/Treatment System (NBS) became operational in 1978 and was expanded in 1981. The Northwest Boundary Containment/Treatment System (NWBS) became operational in 1984. Both systems contain a soil-bentonite slurry wall, a row of extraction wells upgradient of the slurry wall, a water treatment system, and a series of recharge wells on the downgradient side of the slurry wall. The southwest portion of the NWBS does not contain a slurry wall, and groundwater contaminants are captured by a hydraulic barrier established with the extraction and recharge wells. The Irondale Containment/Treatment System (ICS) was activated in 1981 on the western border of RMA and includes two rows of extraction wells, a water treatment system, and a line of recharge wells downgradient of the treatment system.

In 1984, the Army awarded a multiyear, multitask remedial investigation feasibility study (RI FS) contract that included two tasks pertinent to groundwater monitoring: Task 4 and Task 44. Task 4 included a one-year regional groundwater and surface-water sampling program to assess the nature and extent of contamination at RMA and to develop a litigation-quality database. The Initial Screening Program (ISP) was developed to address the technical elements of Task 4. From September 1985 to February 1986, 380 wells were sampled for the ISP that provided basic water quality information for subsequent Task 4 sampling events. A water-level monitoring network of approximately 850 wells was maintained for the ISP. Task 44 provided for water-level and water quality monitoring to identify areas of potentially significant exposure to contamination.

In 1987, long-term groundwater monitoring was separated from the RI FS program and included as a single comprehensive program in the groundwater element of the CMP. The Transitional Monitoring Program was conducted in 1987 to provide continuity between groundwater monitoring for the RI FS contract and the CMP.

The CMP was initiated in 1988 and provided long-term monitoring of groundwater and other environmental media, including surface water, air, and biota. The objectives of the CMP groundwater element were as follows:

- Maintain a regional and local (project area) groundwater monitoring program to update and verify RI FS data.
- Assess and report the amount and extent of contaminant migration and distribution of contaminants both onpost and offpost.

For the 1988 water monitoring year, October 1987 through September 1988, the groundwater element of the CMP included measuring the water level in approximately 1119 wells on a quarterly basis (Table 1.1). The potentiometric surface of groundwater was mapped for six zones in the Denver Formation. In addition, water quality samples were collected from 466 wells for the annual monitoring network, 307 wells for the semiannual monitoring network, and 46 wells for the quarterly monitoring network. Groundwater samples were analyzed for the 59 target analytes listed in Table 1.2.

For the 1989 water monitoring year, October 1988 through September 1989, water levels were measured in approximately 1013 wells on a quarterly basis. The potentiometric surface of groundwater was mapped for six zones in the Denver Formation. In addition, groundwater samples were collected from 488 wells for the annual monitoring network, 388 wells for the semiannual monitoring network, and approximately 50 wells for each of the two quarterly monitoring networks. Groundwater samples were analyzed for the 59 target analytes listed in Table 1.2. Isotopic data for deuterium, oxygen-18, and tritium were collected for a limited number of wells during a pilot program to assess the usefulness of isotopic data to assist in the understanding of the hydraulic connection between the unconfined and confined flow systems.

For the 1990 water monitoring year, October 1989 through September 1990, water levels were measured in approximately 1210 wells on a quarterly basis. The potentiometric surface of groundwater was mapped for six zones in the Denver Formation. In addition, groundwater samples were collected from 621 wells for the annual monitoring network and approximately 60 wells for each of the three quarterly monitoring networks. Groundwater samples were analyzed for the 59 target analytes listed in Table 1.2. Unlike the 1989 water monitoring year, analyses were not performed for isotopes during the 1990 event.

A modification was made to the groundwater sampling networks during the 1990 water monitoring year as a result of assessments of historical trends in analytical data that indicated contaminant migration at RMA not currently undergoing IRA or boundary system cleanups does not change significantly over short time periods of one to two years. The conclusion was made that the frequency of groundwater sampling events could be reduced and still provide adequate contaminant migration assessment. The modification involved changing the annual sampling event (approximately 630 wells) to a biennial (every two years) event with a benchmark well network (approximately 230 wells) to be sampled on alternate years. The benchmark well network is a modification of the former semiannual well network and is a subset of the biennial well network. The benchmark well network allows more frequent (annual) monitoring in selected project areas where interim response actions (IRAs) or other activities have occurred that could cause more rapid changes in contaminant distributions. Quarterly project-specific groundwater sampling will continue to be conducted to support monitoring in the vicinity of the former Basin F.

1.4 OVERVIEW OF CURRENT GROUNDWATER MONITORING

The 1991 water monitoring year is the fourth and final year of the CMP. The GMP will be used during the 1992 water monitoring year to maintain the regulatory database.

The 1991 water monitoring year consisted of three water-level measurement events and three groundwater sampling events. The three events were conducted during Winter 1990/91 and Spring and Fall 1991. Groundwater samples were collected from the CMP benchmark network, which was modified to include 61 additional offpost wells during Winter 1990/91. Groundwater samples were collected from the Basin F IRA area network during Spring and Fall 1991.

2.0 HYDROGEOLOGIC SETTING

The geologic setting of RMA has been described in detail by Morrison-Knudson Engineers, Inc. (MKE) (1988), and Ebasco (1989b), and the groundwater hydrology beneath the site has been described by May (1982). These descriptions will not be repeated here. However, a brief overview of the geologic and hydrologic site conditions is provided to give a framework for understanding the groundwater monitoring system designed for the CMP.

2.1 GEOLOGY

RMA is located within the Denver Basin, a north-south trending syncline. The syncline is asymmetrical with steeply dipping beds that are faulted against the Colorado Front Range on the west and gently dipping beds on the east that extend into western Kansas and southwestern Nebraska. The basin extends from north of Cheyenne, Wyoming, to the south of Colorado Springs, Colorado. RMA is near the structural axis of the southern portion of the syncline where the uppermost beds dip less than one degree to the southeast.

The topography at RMA is expressed as gently rolling hills, wide plains, and shallow basins. The elevation above mean sea level ranges from 5340 feet in the southeastern part of RMA to 5120 feet in the northern part of RMA.

Before the formation of the Denver Basin in its current structural setting, the area near what is now RMA received an influx of various types of sediment as a result of a primarily alluvial depositional environment. The Denver Basin was downwarped to a syncline during the Laramide Orogeny in Late Cretaceous and Early Tertiary time, and the Fox Hills Sandstone, the Laramie Formation, the Arapahoe Formation, and the Denver Formation were deposited (Figure 2.1). Additional alluvial sediment was deposited over the Denver Formation until the late Tertiary period when regional uplift caused the erosion of this additional sediment at RMA, as well as part of the Denver Formation. Subsequently, a variety of Quaternary sediment was deposited at RMA.

This report focuses on the Denver Formation and Quaternary deposits because they contain the principal aquifers in contact with potential contaminant sources within RMA. A claystone layer forms the base of the Denver Formation and provides a confining layer between the Denver Formation and the underlying Arapahoe Formation.

2.1.1 Alluvium

The Quaternary surficial deposits, commonly called the Quaternary alluvium, consist of unconsolidated alluvial and colluvial fill and eolian sand. The alluvial and colluvial material is composed of volcaniclastic material and glacial outwash containing cobbles and boulders in a matrix of clay, silt, sand, and gravel. Older coarse-grained alluvial deposits generally are in areas along the South Platte River and the western part of RMA. Paleochannels eroded into the Denver Formation are also filled with coarse-grained sand and gravel. Younger eolian and alluvial deposits are finer grained than the older surficial deposits and commonly form the uppermost alluvial deposits throughout much of RMA.

The Quaternary alluvium typically ranges from 0 to 50 feet in thickness but locally fills paleochannels to a depth of 130 feet (May, 1982). The surficial geology at RMA is almost entirely alluvial material and the Denver Formation outcrops in only a few locations (Figure 2.2). Eolian deposits occur as a discontinuous thin veneer of sand over most of the surficial material at RMA.

2.2.2 Denver Formation

The Denver Formation is believed to have been originally about 900 feet thick over the RMA area (MKE, 1988), but it has been eroded to a maximum of 500 feet thick in the southeastern corner of RMA. The formation thins to the northwest and is absent beneath the South Platte River, where it has been completely eroded. As much as 40 feet of the upper Denver Formation is weathered and is in direct contact with the Quaternary alluvium.

The Denver Formation consists of a series of interbedded shale and claystone layers enclosing siltstone and sandstone lenses, deposited by low-energy fluvial processes in a continental distal alluvial plain environment. Olive, bluish-gray, and brown colors dominate the upper part of the formation because of lithic fragments derived from the erosion of basaltic and andesitic volcaniclastic material. Sandstone lenses are tan to brown and consist of well-defined fluvial channels and laterally variable crevasse splay sands and overbank deposits. Lignite beds and carbonaceous shales are also present.

Stratigraphic correlation of units within the Denver Formation is difficult because of the discontinuous nature of the sandstone lenses and the lateral variability in thickness and composition of other units. A relatively thick, laterally continuous lignite layer, known as lignite A, occurs within the South Plants and Basin A area. Lignite A has been used as a marker bed from which all other zones in the Denver Formation have been referenced (Ebasco, 1989b). Denver Formation stratigraphy (Figure 2.3) has been interpreted using this and other lignite layers as marker beds.

The Denver Formation dips slightly to the southeast and the erosional bedrock surface slopes to the northwest. Therefore, the stratigraphic units from progressively deeper zones are erosionally truncated to the northwest.

2.2 GROUNDWATER HYDROLOGY

The Denver Basin contains four significant water-bearing hydrostratigraphic units above the thick Pierre Shale aquitard, including those in the Fox Hills Sandstone, the Laramie and Arapahoe Formations, the Denver Formation, and the Dawson Arkose (May, 1982) (Figure 2.1). The main aquifers affected by RMA activity are those in the Quaternary alluvium and the Denver Formation; these are the focus of CMP monitoring efforts.

Groundwater at RMA occurs under both unconfined (at atmospheric pressure) and confined (greater than atmospheric pressure) conditions. The unconsolidated Quaternary alluvium and weathered upper parts of the Denver Formation form a generally continuous groundwater system and the groundwater is typically under unconfined conditions. Confining strata inhibit groundwater interaction between the upper unconfined strata and deeper permeable zones in the Denver Formation, causing confined conditions to exist. To indicate which conditions are present, the groundwater flow systems at RMA are referred to as the unconfined flow system and the confined flow system.

Three water-bearing zones have been defined for the South Plants area by Ebasco (1989a). Each zone consists of a distinct stratum that has a unique potentiometric surface and is separated from the next water-bearing zone by a low-permeability layer. These different zones are described in detail by Ebasco (1989a) and are only briefly described here in the context of CMP monitoring.

Water-bearing zone 1 (WBZ-1) is defined as the uppermost layer of saturated sediment with a unique potentiometric surface. WBZ-1 includes both saturated alluvium and fractured strata of the Denver Formation and is in this way analogous to the unconfined flow system as defined by the CMP. The alluvium of WBZ-1 consists of alternating layers of sandy to gravelly fill, silty to gravelly sand, clay-rich sand, well sorted sand, and silty, gravelly clay. The Denver Formation within WBZ-1 includes weathered claystone, siltstone, sandstone, and volcaniclastic sediment.

Water-bearing zone 2 (WBZ-2) is defined as the second saturated layer below ground surface with a unique potentiometric surface and is analogous to zone A in the confined Denver Formation as defined by the CMP. WBZ-2 consists primarily of fine- to coarse-grained sandstone units with interbedded siltstone and claystone layers of the Denver Formation. WBZ-2 strata subcrop into the alluvium of WBZ-1 in the western portion of the South Plants area, resulting in direct hydraulic communication between the two water-bearing zones. Potentiometric surface elevations in WBZ-2 are generally lower than those in WBZ-1, resulting in a vertically downward hydraulic gradient from WBZ-1 to WBZ-2.

Water-bearing zone 3 (WBZ-3) is defined as the third saturated layer below ground surface with a unique potentiometric surface and is analogous to zone 1U in the confined Denver Formation as defined by the CMP. WBZ-3 includes sandstone and lignite units of the Denver Formation and is bound above and below by claystone. Potentiometric surface elevations of wells screened in WBZ-3 rise 20 to 70 feet above the water-bearing unit (HLA, 1990), indicating confined conditions exist. The potentiometric surface of WBZ-3 is approximately 15 to 50 feet below that of WBZ-2, indicating that the vertical hydraulic gradient is downward.

Ebasco (1989b) has identified 11 distinct zones in the confined flow system within the Denver Formation on the basis of separate depositional sandstone units. The upper six zones (zones A, 1U, 1, 2, 3, and 4) each have a unique potentiometric surface that was measured and used to construct potentiometric surface maps for this report. The zones and their relationship to each other and the alluvium are shown in Figure 2.3.

Groundwater flows to the north and northwest in both the unconfined and the confined flow systems (Figure 2.4). Deviations to the regional flow direction may occur locally as a result of geologic heterogeneities and manmade features, such as the boundary containment systems. The most pronounced deviation to the regional flow pattern is as a groundwater mound in the South Plants area. This mound is approximately 25 feet higher in elevation than the regional water-table surface and coincides with a mound in the bedrock surface. The most probable reason for the existence of the groundwater mound is the relatively low hydraulic conductivity of the bedrock materials that compose the bedrock mound. In addition, recharge from leaky sewers and pipes (Earth Technology Corporation, 1982) has been identified as a possible source contributing to the groundwater mound.

2.2.1 Unconfined Flow System

Groundwater flow occurs in saturated Quaternary alluvium in silt, sand and gravel, glacial outwash, and eolian sand. It is most rapid through alluvium-filled paleochannels incised into the Denver Formation. Groundwater flow occurs primarily in the saturated alluvium, which generally has a higher hydraulic conductivity and transmissivity than the unconfined Denver Formation. The unconfined flow system has a saturated thickness of up to 70 feet, with the greatest thickness occurring in the alluvium-filled paleochannels in northwestern RMA. Beneath the South Plants and the waste basins, the saturated thickness of the unconfined flow system is typically less than 20 feet.

Recharge to the unconfined flow system occurs primarily from infiltration of precipitation and irrigation, seepage from lakes and streams, and inflows from subcropping confined Denver Formation zones. Leakage from manmade structures, such as the manufacturing complexes, chemical and sanitary sewer systems, basins, canals, and buried pipelines, contribute a lesser amount to groundwater recharge.

Groundwater discharge from the unconfined flow system occurs primarily into the South Platte River, northwest of RMA, but may also occur into the lakes and ponds on RMA and into First Creek near the northern RMA boundary. Evapotranspiration may occur where the water table is near the land surface.

2.2.2 Confined Flow System

Groundwater flow in the Denver Formation occurs primarily in permeable sandstone, siltstone, and lignite. The permeable strata in the Denver Formation are discontinuous, which results in hydraulic separation into distinct aquifer zones. Water also may flow locally along fracture systems in shale and claystone, which otherwise form confining layers.

Hydraulic head in the confined flow system decreases with increasing depth in most locations at RMA. As a result, recharge to the confined flow system is likely to occur by leakage from overlying strata. The presence of this recharge is supported by inorganic chemical and isotopic evidence (Stollar, 1990a). Recharge also occurs by lateral flow in Denver Formation units from areas south and east of RMA. Regional groundwater flow in the confined flow system is up dip to the northwest. Groundwater flow is the result of greater precipitation and enhanced recharge along streams in upland areas of the Denver Basin (e.g., Castle Rock area), combined with discharge to low points in the Denver Basin (e.g., South Platte River) and pumping. Discharge from the confined flow system occurs by lateral flow into the unconfined flow system where permeable zones subcrop.

3.0 PROGRAM STRATEGY

The groundwater monitoring activities performed during the 1991 water monitoring year were designed to meet the CMP objectives discussed in Section 1.3 of this report. Three monitoring events were performed during the 1991 water monitoring year: one each during Winter 1990/91 and Spring and Fall 1991. During each event, water levels were measured first, then groundwater samples were collected for chemical analyses. No groundwater monitoring events occurred for the CMP during Fall 1990 or Summer 1991.

This section describes the water-level measurement and groundwater sampling networks used during 1991 water monitoring year events and explains how they compare to previous networks. This section also briefly describes the procedures followed to measure water levels and collect groundwater samples and the QA/QC measures taken to ensure the accuracy of the results.

3.1 WATER-LEVEL MONITORING

Water-level data are important in assessing groundwater and contaminant movement. As part of the CMP, water levels in approximately 1200 monitoring wells are measured quarterly before each groundwater sampling event to provide seasonal information on potentiometric surfaces in the unconfined and confined flow systems. The water-level monitoring network is designed to allow collection of data to assess both regional and local (project area) groundwater flow conditions.

3.1.1 Network Design

The water-level monitoring network was designed to provide the most efficient areal coverage throughout RMA and in the offpost area to allow assessment of groundwater levels for both the unconfined and confined flow systems. The majority of wells were selected for inclusion in the water-level monitoring network during a series of sessions attended by technical representatives of the Army, Shell, and their contractors. The same wells continue to be included in the CMP water-level monitoring network to provide continuity to the water-level database and to allow comparison to historical trends. New wells, installed to monitor IRA cleanup areas, are incorporated into the network. Wells are deleted from the network as they are abandoned or destroyed. For the 1991 water monitoring year, water levels were measured in 1171 to 1216 wells.

Selection criteria for wells to be included in the water-level monitoring network were similar for both the unconfined and confined flow systems. The current condition of the well and historical water-level data were reviewed and the areal distribution of wells was evaluated. Wells that were destroyed or abandoned and wells with obstructions that prevent the water level from being measured were deleted from the network. Some historically dry wells were retained in the network to monitor potential water-table changes that could occur in response to IRA activities or seasonal fluctuations.

The water-level monitoring network was developed to maximize areal and vertical coverage. Wells were selected from both the unconfined and confined flow systems. Wells in clusters were preferentially selected to provide information on the vertical interaction between aquifer zones. Because the confined flow system contains fewer wells and because groundwater interaction patterns between zones are complex, a high percentage of existing confined flow system wells were selected to be in the water-level monitoring network. A list of water-level measurements recorded during the 1991 water monitoring year, from the current CMP water-level monitoring network, is included in Appendix A (on diskette). The Winter 1990/91 water-level monitoring networks for the unconfined and confined flow systems are shown on Plate 2 and in Figure 3.1, respectively.

3.1.2 <u>Comparison With Previous Networks</u>

One goal of the CMP is to consistently use the same wells to ensure that quarterly data are comparable. However, the network changes slightly from year to year to include newly installed wells and to delete wells that have been abandoned or destroyed. The core wells that constitute the CMP water-level monitoring network were initially selected from the Spring 1987 monitoring period from RI/FS Tasks 25 (NBS and NWBS monitoring networks) and 44 (regional monitoring network, including the ISP monitoring network). The network has consistently grown since the

CMP began in 1988. The water-level monitoring network consisted of 1265 wells during the 1991 water monitoring year. The number of wells actually measured is less than 1265.

3.1.3 Procedures

Standard field procedures have been established to achieve consistency and reliability in water-level measurements. These procedures are described in detail in the Rocky Mountain Arsenal Continuous Monitoring Program Ground Water Procedures (Stollar and others, 1990a) and briefly repeated here. An electronic conductivity probe is used to measure the depth to water from the top of the inner well casing (TOC). The water-level elevation at each well is calculated using the field measurements and previously surveyed TOC elevations.

3.1.4 Quality Assurance and Quality Control

QA/QC procedures have been established to ensure the precision, accuracy, representativeness, consistency, and defensibility of results. Field documentation procedures are detailed in the Rocky Mountain Arsenal Comprehensive Monitoring Program QA/QC Plan (Stollar and others, 1988).

QA/QC is performed on water-level measurements through field observations and review of historical data. While at the well, site conditions are recorded that could account for a discrepancy between current and previous measurements, such as subsidence features, broken casings, and downhole obstructions. The height of the well casing from ground level to the TOC, the depth to water, and the total depth of dry wells are compared to the previous measurements for each well. If unexplained discrepancies exist, field rechecks are performed to verify the measurement in question.

3.2 GROUNDWATER SAMPLING

Groundwater samples are collected and analyzed for contaminants to assess current contaminant distribution, changes in contamination patterns, and rates of contaminant migration. During the 1991 water monitoring year, groundwater samples were collected and analyzed to assess contaminant distribution for various IRA project areas in both the unconfined and confined

Denver Formation flow systems. The IRA project areas that are the focus of this report are the NBS, NWBS, the Basin A Neck Containment System (BANS), and the Basin F IRA area. In addition, the ICS was assessed, although the available data allowed only a cursory review of this system.

3.2.1 Network Design

The CMP groundwater sampling network was modified in 1990 to create a benchmark well network to be sampled on a biennial basis and to eliminate the semiannual monitoring event, as presented in the CMP Draft Final Technical Plan Addendum (Stollar and others, 1990b). This change was based on previous RMA groundwater monitoring data that indicated that the regional distribution of contaminants did not change significantly on an annual basis in areas unaffected by current IRA and boundary containment system activities. The benchmark well network is essentially the project area network that was monitored during Winter 1990/91. The benchmark network allows more frequent monitoring, at least annually, in areas where IRAs have been undertaken.

The groundwater sampling networks for the 1991 water monitoring year were designed to (1) monitor a network of 282 wells in specific project areas during the benchmark event and (2) monitor a Basin F IRA area network of 70 wells two times per year in addition to the benchmark event. The benchmark network was designed to monitor four IRA areas: the NBS, the NWBS, the BANS, and the Basin F IRA area. During Winter 1990/91, 61 offpost wells were added to the benchmark monitoring network to provide assessment of contaminant migration offpost that may be associated with RMA activity. Future benchmark networks will not include the sampling of these 61 offpost wells.

The network well selection criteria for the CMP were described in detail in the CMP Technical Plan (Stollar and others, 1989b). In general, wells were selected for the CMP groundwater sampling network if they had been included in previous networks and therefore had historical water-quality data, were in good condition, or were in a well cluster. Wells were also chosen for inclusion in the network on the basis of their location and the zone in which they are screened. Wells upgradient of contaminant plumes were monitored to assess background analyte concentrations. Wells downgradient of known plumes were monitored to assess the location and movement of leading edges of contaminant plumes. Wells with screened intervals in different hydrologic zones were selected to obtain information on the vertical extent of contamination.

During Winter 1990/91, samples were collected from 282 benchmark network wells (213 unconfined flow system wells and 69 confined Denver Formation flow system wells) on RMA and in downgradient offpost areas (Table 3.1, Figures 3.2 and 3.3). Nine wells were not sampled as planned because of insufficient recharge or dry well conditions. Wells in the benchmark network (including the Basin F IRA area network) were sampled during Winter 1990/91 from early February through mid-March 1991.

The Basin F IRA area monitoring well network was sampled again in April (Spring) and October (Fall) 1991. The Basin F IRA area is monitored more frequently than are the other networks to comply with substantive regulatory requirements. The monitoring well network included 70 wells (47 unconfined flow system wells and 23 confined Denver Formation flow system wells), as listed in Table 3.1 and shown in Figure 3.4. Nine wells in Spring and 12 wells in Fall were not sampled as planned because of insufficient recharge or dry well conditions.

3.2.2 Comparison With Previous Networks

The CMP well network has evolved from previous regional and project-specific RMA monitoring networks as described in Section 1.3 and has changed over time during the CMP, as described below. The approach to water quality monitoring used during the CMP consisted of sampling at three levels of detail and at varying frequencies, as outlined below:

- Regional monitoring network. This includes a regional network of monitoring wells that was sampled annually during the CMP. The purpose of this network is to provide a comprehensive regional assessment of contaminant plumes and migration characteristics over time. This network consisted of approximately 470 wells during the 1988 water monitoring year and has increased in size during the CMP to approximately 620 wells during the 1990 water monitoring year. This network has been changed to a biennial (once every two years) monitoring schedule.

- Semiannual monitoring network. This network, a subset of the regional monitoring network, monitors wells around specific project areas, such as the boundary containment systems and IRA areas. The purpose of this network is to provide project-specific information in areas where remediation activities may be causing contaminant distributions to change more rapidly than would be expected under normal regional groundwater flow conditions. This network was sampled at six-month intervals between sampling events of the regional monitoring network. This network consisted of approximately 310 wells during the 1988 water monitoring year and 390 wells during the 1989 water monitoring year. This network included approximately 230 wells during the 1991 water monitoring year. During 1991 and subsequent years, this network will be referred to as the benchmark network and it will be monitored once every two years, on alternate years from the regional monitoring network.

- Quarterly monitoring network. This network, a subset of both the regional and benchmark monitoring networks, includes wells in a project-specific IRA area that are monitored on a more frequent basis to comply with substantive regulatory requirements. This network is the smallest monitoring network. The number of wells being monitored has fluctuated between 46 and 65 wells during previous CMP monitoring years. This network was referred to as the Basin F IRA area monitoring network during the 1991 water monitoring year, when 69 wells were included in the network and as a subset of the regional monitoring network.

3.2.3 Procedures

The groundwater sampling procedures followed during the CMP are consistent with the methods outlined in the Chemical Quality Assurance Plan (CQAP) (PMRMA, 1989). The procedures used for groundwater sampling are described in detail in the Rocky Mountain Arsenal Continuous Monitoring Program Ground Water Procedures (Stollar and others, 1990a) and are briefly described here:

- Water level is measured.
- The well is purged by removing five casing volumes of water.
- Groundwater samples are collected in containers specified by PMRMA.
- Groundwater samples are sent to designated laboratories for chemical analyses.

3.2.4 Chemical Analysis

The groundwater samples collected during the 1991 water monitoring year were analyzed using the PMRMA-certified methods for the analytes listed in Table 3.2. Analyses were performed at DataChem Laboratories (Salt Lake City, Utah) or ESE Laboratories (Denver, Colorado, and Gainsville, Florida). The certified reporting limit (CRL) for each analyte can vary between laboratories, as seen in Table 3.2. Concentrations of all analytes detected by non-gas chromatography/mass spectrometry (GC/MS) methods are presented by site identification (ID) number in Appendix B of this report (on diskette). Non-GC/MS methods include colorimetric, high performance liquid chromatography (HPLC), ion chromatography (IONCHROM), atomic absorption spectrometry (AA), inductively coupled argon plasma screen (ICP), and gas chromatography by the conductivity detector (GC/CON), the electron capture detector (GC/ECD), the flame ionization detector (GC/FID), the flame photometric detector (GC/FPD), the nitrogen phosphorus detector (GC/NDP), and the photoionization detector (GC/PID).

Groundwater samples for GC/MS analysis were collected only during the Spring 1991 sampling event from approximately 20 percent of the wells sampled. GC/MS analyses were performed at both DataChem and ESE laboratories. The CRLs for CMP target analytes for the GC/MS method are listed in Table 3.3. GC/MS analyses were performed to confirm the presence of target analytes detected by non-GC/MS methods. GC/MS analyses were also used to detect the presence of nontarget analytes. Tentative identification of nontarget analytes was made, when possible, on the basis of spectral analysis. When nontarget analytes are positively identified and consistently detected at elevated levels during the CMP, they are reviewed for potential inclusion as target analytes. Appendix C presents the results of GC/MS analyses for the 1991 water monitoring year.

3.2.5 Quality Assurance and Quality Control

The QA/QC Plan (Stollar and others, 1988) implemented for groundwater sampling procedures during the CMP is consistent with the procedures outlined in the CQAP (PMRMA, 1989). The objectives of the QA program for the RMA CMP are as follows:

- Ensure that technically defensible and consistent sample collection procedures are used.
- Document procedures used in the collection, preservation, and handling of samples.
- Collect additional samples such that data accuracy, precision, and representativeness may be assessed.
- Perform chemical analyses of all samples, including those collected for QC, according to documented certified procedures that will ensure data validity.

Field and sampling procedures are established to ensure consistency of methods for legally defensible data. Procedures are established for purging the well, monitoring sample parameters (temperature, pH, electrical conductivity, alkalinity, and dissolved oxygen), sampling, and decontaminating equipment. Daily field activities were documented by maintaining a field logbook, a separate field data sheet for each well, and a chain-of-custody (COC) form that accompanies the sample from collection to the analytical laboratory.

Additional groundwater samples were collected to assess the accuracy, precision, and representativeness of the analytical data. Duplicate and blank samples were collected during each sampling event. Duplicate samples were collected at a rate of approximately 10 percent of total investigative samples to monitor the consistency of sampling procedures and analytical results.

Trip, field, and rinse blanks were each collected at a rate of 5 percent of total investigative samples during each sampling event. Field blanks consist of a full suite of sample bottles filled with distilled water at the field site. The field blank bottles remain uncapped during collection of the regular investigative sample. Field blanks are used to assess whether contamination is being introduced into samples through windblown dust, ambient air, or sampling procedures. Trip blanks consist of four 40-milliliter sample bottles filled by the laboratory with distilled water. Trip blanks are normally analyzed for volatile organic compounds only; however, during the 1991 water monitoring year, trip blanks were analyzed for the entire target analyte list. Trip blanks are transported to the field site and carried, unopened, with the regular investigative samples during transport and shipment. Trip blanks are used to assess whether contamination is being introduced by volatile organic compounds during transportation of the samples. Rinse blanks are collected in the field to assess the adequacy of field decontamination procedures. Rinse blanks are obtained by running distilled water through sample collection equipment after decontamination and collecting it in a full suite of sample containers for analysis.

4.0 RESULTS OF MONITORING DURING THE 1991 WATER MONITORING YEAR

This section describes the results of water-level monitoring and groundwater sampling events during the 1991 water monitoring year. Section 4.1 describes water-level monitoring efforts and results, and Section 4.2 describes groundwater sampling activities and results. Section 4.3 summarizes the data for both the unconfined and confined flow conditions and presents conclusions regarding hydraulic interaction between the systems. All data presented in this report that were collected during the 1991 water monitoring year are provided on diskette in the appendixes to this report. Appendix A lists the hydrogeologic data collected during the 1991 water monitoring year. Appendix B lists the GC data, and Appendix C lists the GC/MS data collected during the 1991 water monitoring year. A summary of field data collection efforts for the 1991 water monitoring year is provided below.

Season	Number of Wells in Which Water Levels Were Measured	Dates of Measurements	Number of Water Quality Wells Proposed	Number of Water Quality Wells Sampled	Water Quality Sampling Dates
Winter 1990/91	1216	01/23/91 to 02/04/91	282	273	02/05/91 to 03/11/91
Spring 1991	1171	04/01/91 to 04/09/91	70	61	04/10/91 to 04/19/91
Fall 1991	1177	09/16/91 to 09/27/91	70	58	09/30/91 to 10/18/91

Groundwater samples were collected during three events in the 1991 water monitoring year. The Winter 1990/91 sampling event represents the benchmark network, and Spring and Fall 1991 sampling events represent the Basin F IRA network. The results of these efforts are described in Section 4.2. Groundwater samples were analyzed for 59 target analytes during the 1991 water monitoring year. Analytical results are provided in Appendixes B and C.

For the purpose of graphical presentation in this report and assessment of contaminant distribution in the IRA areas, five contaminants were selected for discussion: diisopropylmethylphosphonate (DIMP), dibromochloropropane (DBCP), chloroform, dieldrin, and fluoride.

These contaminants were used in the assessment of contaminant distribution because they represent a range of contaminant mobilities, are of particular importance in assessing IRA performance, and/or are representative of different types of contaminants present on RMA. DIMP and dieldrin are two of the most widespread and consistently detected semivolatile compounds for which analyses were performed, and they represent a wide range in behavior in the environment and in toxicity. DIMP is highly mobile and of low toxicity. In contrast, dieldrin has low solubility and is relatively immobile in groundwater but has comparatively high toxicity. Dieldrin is also representative of the organochlorine pesticide compounds. Chloroform and DBCP are the most widespread and consistently detected volatile organic compounds. These two contaminants are also important in assessing the efficacy of the NBS and NWBS. Fluoride is representative of inorganic constituents and is also a naturally occurring anion in groundwater. The assessment of fluoride contamination in the groundwater at RMA includes a comparison with a concentration that is considered representative of background fluoride levels at RMA.

4.1 WATER-LEVEL MONITORING DATA

Water-level measurements obtained during the three monitoring periods of the 1991 water monitoring year were integrated with well coordinate and elevation data to produce water-table maps of the unconfined flow system and potentiometric surface maps of the six uppermost confined Denver Formation zones. Two water-table maps of the unconfined flow system were prepared for each monitoring period: one illustrates the regional water table (Figures 4.1, 4.2, and 4.3) and the other presents a more detailed configuration of the water-table surface in the northern IRA areas (Figures 5.2, 5.3, and 5.4). The northern IRA area includes the NBS, NWBS, Basin F IRA area, BANS, and ICS.

In addition to the CMP data, water-level measurements recorded by the Technical Operations Division (TOD) of the Army and MKE were used for wells that were important in assessing the IRA areas but were not measured as part of the CMP network. When these data were used, they were selected to correspond to the date of the closest CMP monitoring event for each area. Data collected more than two weeks before or two weeks after the CMP monitoring events were not incorporated in the regional water-level maps. The TOD data used were collected from a denser well network than the CMP network to provide frequent water-level information in support of operating the NBS. The MKE data used were collected from the boundary containment/treatment systems in association with IRA improvements on the NBS and NWBS.

4.1.1 Unconfined Flow System

Water-level data from wells screened in the alluvium and upper unconfined portions of the Denver Formation were used to construct three unconfined flow system water-table elevation maps. Figures 4.1 through 4.3 illustrate the regional water-table surface at RMA for each of the three monitoring periods during the 1991 water monitoring year. The majority of water-level measurements used to construct the water-table elevation maps were collected for the CMP; however, concurrent data collected by TOD, MKE, and USGS at wells not measured for the CMP were used to supplement data and aid in interpretation of the water-table surface at the NBS and the NWBS (discussed in Section 5.0).

The Winter 1990/91 water-table map (Figure 4.1) shows areas where the alluvium is interpreted to be unsaturated. In areas of unsaturated alluvium, groundwater flow in the unconfined flow system is within the upper portion of the Denver Formation. Areas of unsaturated alluvium were defined by subtracting the elevation on the Winter 1990/91 contoured head map from the elevation on the bedrock surface map. Areas of saturated alluvium occur where the head elevation is greater than the bedrock elevation. Limited QC of the areas of saturated alluvium was performed by calculating the saturated thickness at wells. The bedrock surface map used to assess the areas of unsaturated alluvium was based on a composite map generated from bedrock maps prepared by ESE (1988a), MKE (unpublished map for Sections 1, 2, 25, 35, and 36), Woodward-Clyde Consultants (1990), and HLA (1990). Therefore, Figure 4.1 shows the Army's current conceptualization of unsaturated alluvial areas using new survey data, but it does not imply that exhaustive review and revision of previous geologic interpretations of the bedrock surface has been conducted.

As illustrated in Figures 4.1 to 4.3, the regional slope of the water table at RMA is from southeast to northwest. The drop in the water-table elevation across RMA is approximately 200 feet. Regional groundwater flow is to the northwest, and the average hydraulic gradient is approximately 0.006. The water table intersects the South Platte River about 2 miles northwest of RMA. The river acts as the regional discharge area for the unconfined flow system.

In general, the configuration of the water table at RMA roughly resembles the configuration of the bedrock surface. Areas of relatively thick and uniform alluvium have a regular and gently sloping water table. This situation occurs in the eastern and southeastern portions of RMA and to the northwest of RMA. The central portion of RMA, which is characterized by relatively thin and uneven alluvium overlying an irregular bedrock surface containing paleochannels, has an irregular water-table surface and some relatively steep hydraulic gradients.

The most pronounced anomaly in the regional trend of the water-table surface at RMA is the groundwater mound beneath the South Plants Manufacturing Complex. This mound is approximately 20 to 30 feet higher in elevation than the regional water-table surface, and it coincides with a mound in the bedrock surface that occurs beneath the South Plants area. This bedrock mound subcrops near the center of the South Plants area, where the alluvium is thin to absent.

Along the north and northwest boundaries of RMA, the water table is modified by the presence of a soil-bentonite barrier wall at the NBS and NWBS and by the operation of the systems. The water table in the vicinity of these systems is discussed in Sections 5.1 and 5.2. In western RMA, operation of the ICS and the creation of a hydraulic barrier have caused local deviations in the water table, which are discussed in Section 5.5.

The general level of the regional water-table surface remained relatively constant from Winter 1990/91 through Spring 1991. Water-table fluctuations, which yielded approximately 5-foot higher water levels during Winter 1990/91 than Spring 1991, were southwest of the ICS in Section 33 and along the north side of the Burlington Ditch in Section 22. Directly north of the NBS in Sections 24 and 13, water levels were as much as 5 feet higher in Spring 1991 than in

Winter 1990/91. Water-level fluctuations were generally less than 1 foot over the south, central, and eastern portions of RMA.

The regional water table fluctuated more between Spring and Fall 1991 than between Winter 1990/91 and Spring 1991. Southwest of the ICS in Section 33, water levels were 9 feet higher in Spring 1991 than in Fall 1991. Along the north side of the Burlington Ditch in Section 22, water levels were 9 feet higher in Fall 1991 than in Spring 1991. Water levels were as much as 6 feet higher in Fall 1991 than in Spring 1991 in the South Plants area in Section 1.

4.1.2 Confined Flow System

The potentiometric surfaces of the six uppermost Denver Formation confined flow system zones (A, 1U, 1, 2, 3, and 4) were interpreted from water-level measurements recorded during Winter 1990/91. The six potentiometric maps for zones A through 4 are presented in Figures 4.4 through 4.9, respectively. Potentiometric maps of the confined flow system are not presented for the other seasons because the potentiometric surfaces do not vary significantly.

The general direction of groundwater movement is to the northwest in all six confined flow system zones. The bedrock high in the South Plants area appears to have influenced the groundwater flow in zones A and 1U of the confined flow system, as illustrated in Figures 4.4 and 4.5, respectively. Within zone A, a groundwater mound is interpreted to exist in Section 1 that is 5 feet higher than the regional potentiometric surface of zone A. Within zone 1U, a groundwater mound is interpreted to exist in the vicinity of Basin A (Sections 35 and 36) that is as much as 15 feet higher than the regional potentiometric surface of zone 1U. Additional deviations in the potentiometric contours are present in the vicinity of the Basin A Neck in zones 1U, 1, and 2 of the confined flow system, as shown in Figures 4.5 through 4.7, respectively. The potentiometric surface anomalies appears to become less prominent with depth in both of these areas. However, fewer wells are completed below the Denver Formation in zone 1 and less control exists over the potentiometric surface contours.

The potentiometric surface elevations in confined zones in the Denver Formation generally decrease with succeedingly lower zones. The amount of difference between potentiometric surface elevations also generally decreases with succeedingly lower zones.

The regional horizontal hydraulic gradient of the potentiometric surface for the six confined flow system zones is generally less than the regional gradient of the unconfined flow system water-table surface, except for the gradient in zone 1. The regional gradient of the potentiometric surface averages approximately 0.004 for zones 1U and 2, approximately 0.005 for zones A and 3, approximately 0.0065 for zone 4, and approximately 0.007 for zone 1.

4.1.3 Influences on Data Interpretation

The interpretation of water-level data collected during the 1991 water monitoring year was influenced by several variables that may cause varying interpretations as a function of the network used and the accuracy of the data. These variables included the number and location of monitoring wells in the network and the use of updated survey data.

4.1.3.1 Monitoring Network

There were few changes in the number and distribution of wells included in the CMP regional water-level monitoring network between the 1990 and the 1991 water monitoring years. A few wells measured in the 1990 water monitoring year were destroyed or abandoned during the 1991 water monitoring year. However, no new wells were added to the network. The addition of supplemental TOD, MKE, Shell, and U.S. Geological Survey (USGS) data provided a larger set of water-level data than was utilized in previous years, but because the use of this information was restricted to the boundary system areas, it had only local impact. These modifications created only relatively small changes to the interpretation of water-table or potentiometric data between the 1990 and 1991 water monitoring years. The number of wells included in the water-level networks for the 1988, 1989, 1990, and 1991 water monitoring years are summarized in Table 4.1.

4.1.3.2 Updated Survey Data

During the 1991 water monitoring year, MKE resurveyed approximately 510 well locations and elevations in Sections 1, 2, 25, 26, 35, and 36. The new TOC elevation data included about 50 changes of more than 1 foot compared to previously used CMP data. Changes of up to 11.25 feet were recorded. Use of the new TOC data changed the interpretation of the water-table surface and, to a lesser extent, the potentiometric surfaces of the confined zones at some locations.

4.2 GROUNDWATER SAMPLING DATA

Analytical data from the 1991 water monitoring year were used to assess variations in contaminant distributions in project areas compared to previous years. This comparison was accomplished by focusing on the distributions of five selected analytes: DIMP, DBCP, chloroform, dieldrin, and fluoride. Tables 4.2, 4.3, and 4.4 summarize the analytical results for all CMP target analytes for Winter 1990/91, Spring 1991, and Fall 1991, respectively. Analytical data for the five selected analytes are summarized in Tables 4.5 and 4.6. Appendixes B and C contain all analytical data for all CMP target analytes collected during the 1991 water monitoring year. Appendix B contains analytical data collected by GC methods, and Appendix C contains data collected by GC/MS analyses. Winter 1990/91 analytical data for the confined and unconfined flow systems are presented by posting analytical results from the 1991 water monitoring year on contaminant plume maps that were generated using Fall 1989 analytical results (Stollar and others, 1991).

Seventy percent (274) of the groundwater samples collected during the 1991 water monitoring year were sent to the DataChem Laboratories in Salt Lake City, Utah, for analysis. DataChem performed the analyses for the complete CMP analytical suite for all samples except 16 samples for which ESE-Denver performed the anion analyses. Analyses for nitrogen-phosphorous pesticides for the remaining 118 samples were performed at the ESE laboratory in Gainesville, and the analyses for the remaining suite were performed at the ESE laboratory in Denver.

4.2.1 Contaminant Distribution in the Unconfined Flow System

The areal extent of the five selected compounds in the unconfined flow system is discussed in the subsections that follow. A similar discussion for the confined flow system is presented in Section 4.2.2. The use of the benchmark network during the Winter 1990/91 monitoring event limits comparison of Fall 1989 and Winter 1990/91 data to project areas. Therefore, although 1990 water monitoring year plume maps are presented for the entire regional area, comparisons were made only in project areas. In the project areas, remediation activities may have caused more rapid changes in contaminant distribution than in areas where the groundwater flow system is under natural regional conditions.

4.2.1.1 Diisopropylmethylphosphonate (DIMP)

Analyses for DIMP were performed on 260 groundwater samples collected from the unconfined flow system during the 1991 water monitoring year. DIMP was reported in 203 (78 percent) of the samples at concentrations ranging from 0.513 to 5400 micrograms per liter ($\mu g/l$). The majority of the samples (188) for DIMP from the unconfined flow system were collected during Winter 1990/91. DIMP was reported in 36 (19 percent) of these samples at concentrations ranging from 0.513 to 3700 $\mu g/l$. Figure 4.13 shows Fall 1989 DIMP plumes in the unconfined flow system with the Winter 1990/91 analytical results posted.

In general, the Winter 1990/91 analytical results are consistent with the contoured concentration from Fall 1989 plumes. DIMP occurs over a continuous area from the South Plants north and northwest to offpost areas north of RMA (Figure 4.13). Results for eight wells, which are in the offpost areas north of RMA, were sampled in Winter 1990/91 but not in Fall 1989 and indicate concentrations above the inferred concentration from the Fall 1989 plume map for DIMP. Results for other wells in this area also show concentrations that are higher than the contoured areas shown for the Fall 1989 plume map for DIMP.

4.2.1.2 Dibromochloropropane (DBCP)

Analyses for DBCP were performed on 218 groundwater samples collected from the unconfined flow system during the 1991 water monitoring year. DBCP was reported in 39 (18 percent) of these samples at concentrations ranging from 0.147 to 71.0 μg/l. The majority of the samples (145) from the unconfined flow system for DBCP were collected during Winter 1990/91. DBCP was reported in 20 (14 percent) of these samples at concentrations ranging from 0.147 to 15.0 μg/l. Figure 4.12 shows the Fall 1989 DBCP plumes with the Winter 1990/91 analytical results posted.

In general, Winter 1990/91 analytical results for DBCP are consistent with the concentrations indicated by the Fall 1989 data. However, in the project areas near the ICS, Basin F, and north of the NBS, some anomalies were evident, but these anomalies would not significantly alter the general plume configurations. Near the ICS, one well had a higher DBCP concentration than indicated by the Fall 1989 plume map. When this well (33581) was sampled in Fall 1989, DBCP concentrations were less than the CRL; therefore, the results were inconsistent with the Winter 1990/91 results. In the vicinity of Basin F, a DBCP concentration of 7.79 μg/l was reported in Section 23, which would extend the plume area and show higher contaminant concentrations to the northeast. Concentrations of DBCP south and north of the northern pathway plume in Sections 13 and 11 may indicate that this plume is slightly more areally extensive than previously thought. In the First Creek pathway, DBCP was reported in Section 14 outside the 1990 plume boundaries. However, existing data indicate that these wells may represent only isolated DBCP detections because DBCP concentrations at these wells were less than the CRL in Fall 1989.

4.2.1.3 Chloroform

Analyses for chloroform were performed on 270 groundwater samples collected from the unconfined flow system during the 1991 water monitoring year. Chloroform was reported in 132 (49 percent) of these samples at concentrations ranging from 0.573 to 73,000 μg/l. The majority of these samples (205) were collected during Winter 1990/91. Chloroform was reported in 97

(47 percent) of these samples at concentrations ranging from 0.573 to 22,000 μg/l. Figure 4.11 shows Fall 1989 chloroform plumes in the unconfined flow system with the Winter 1990/91 analytical results posted.

In general, the 1991 water monitoring year values for chloroform are consistent within the plumes delineated in the 1990 water monitoring year. However, some differences do exist. The 1991 water monitoring year data suggest that chloroform contamination extends farther downgradient along the northwest offpost pathway than indicated by previous CMP data. This is shown by detections ranging from 1.60 to 2.93 μg/l in three wells in Sections 15 and 16 north of the northwest pathway. In the First Creek pathway, chloroform was reported in four wells in Section 14 that were outside the plume boundaries contoured for 1990. However, an extended plume beyond this area to near Highway 2 does not appear to exist. Finally, two anomalies were noted in the northern pathway. First, two samples from wells within the 100 μg/l contour had reported concentrations less than 10 μg/l. Second, three samples from wells near the leading (northern) edge of the plume, southeast of O'Brian Canal in Section 11, all appear to have higher concentrations of chloroform than would be expected based on the 1990 plume configuration. This trend will be reviewed during the 1992 water year monitoring. The data also suggest that in the northern offpost pathway, the chloroform plume extends as far upgradient as the NBS, whereas Fall 1989 data indicated the chloroform plume did not extend to the NBS.

4.2.1.4 Dieldrin

Analyses for dieldrin were performed on 191 groundwater samples collected from the unconfined flow system during the 1991 water monitoring year. Dieldrin was reported in 76 (40 percent) of these samples at concentrations ranging from 0.0457 to 7.40 μg/l. The majority of these samples (124) were collected during Winter 1990/91. Dieldrin was reported in 29 (23 percent) of these samples at concentrations ranging from 0.0452 to 3.30 μg/l. Figure 4.10 shows Fall 1989 dieldrin plumes in the unconfined flow system with the Winter 1990/91 analytical results posted.

In general, the values for dieldrin in the unconfined flow system were consistent with the Fall 1989 plume configurations, and where contaminants were detected outside Fall 1989 plume boundaries, they varied from the CRL by less than a factor of two. One exception to this was a value of 0.323 μg/l outside the plume boundary in Section 2. This value is consistent with previous values reported for this well (02023). Previous interpretations have identified this well as an isolated detection.

4.2.1.5 Fluoride

Analyses for fluoride were performed on 204 groundwater samples collected from the unconfined flow system during the 1991 water monitoring year. Fluoride was reported in 164 (80 percent) of the samples at concentrations ranging from 832 to 25,000 μg/l. The relative low percentage of detections for fluoride is because of the high certified reporting limits that are necessary because of method variations and dilutions. The majority of these samples (129) were collected from the unconfined flow system during Winter 1990/91. Fluoride was reported in 120 (93 percent) of these samples at concentrations ranging from 832 to 13,000 μg/l. Figure 4.14 shows Fall 1989 fluoride plumes in the unconfined flow system with the Winter 1990/91 analytical results posted.

Fluoride is a naturally occurring constituent of groundwater. Samples collected upgradient of RMA between 1964 and 1976 reported fluoride concentrations ranging from 570 to 4850 μg/l, indicating that background concentrations may be highly variable. The background concentration of fluoride estimated from 1989 data in wells upgradient of RMA was 1390 μg/l (Stollar and others, 1991). Technical Operations Division (TOD) of PMRMA is currently assessing whether reported fluoride concentrations may be biased high in the presence of high chloride concentrations. A new laboratory method (ion-selective) is to be used to analyze fluoride. Results from this new fluoride method were not available for inclusion in this report.

In general, the Winter 1990/91 analytical results for fluoride are similar to the concentrations defined by the Fall 1989 contours. Wells sampled in Winter 1990/91 but not in Fall 1989 indicate concentrations above the contoured concentration in some of the northern offpost areas and in

Sections 26 and 35 onpost (near the Basin A Neck system). Two wells in Section 23 near Basin F show lower concentrations in Winter 1990/91 than in Fall 1989.

4.2.2 Contaminant Distribution in the Confined Flow System

The areal extent of the five selected compounds in the confined flow system is discussed in the subsections that follow. Isoconcentration maps were not created because of the limited number of wells in the Denver Formation confined zones. As noted in Section 4.2.1, the sampling network for the 1991 water monitoring year was designed to focus on project areas. Therefore, specific comparisons presented in the following discussions apply only to areas where 1991 water monitoring year data are available.

4.2.2.1 Diisopropylmethylphosphonate (DIMP)

Analyses for DIMP were performed on 104 samples collected from the confined flow system during the 1991 water monitoring year. DIMP was reported in 23 (22 percent) of these samples at concentrations ranging from 0.443 to 1900 $\mu g/l$. Sixty of the samples were collected during the Winter 1990/91 sampling. DIMP was reported in 15 (25 percent) of these samples at concentrations ranging from 0.443 to 1900 $\mu g/l$. Figure 4.18 shows Winter 1990/91 DIMP detections within the confined flow system. Slight changes were noted in three onpost wells and several offpost wells between Fall 1989 and Winter 1990/91. DIMP was also detected in three newly installed offpost IRA wells completed in the unconfined flow system. The maximum depth from which a positive DIMP detection was derived was from well 37319 at a depth of 155.0 feet below ground surface.

4.2.2.2 Dibromochloropropane (DBCP)

Analyses for DBCP were performed on 84 samples collected from the confined flow system during the 1991 water monitoring year. DBCP was reported in 3 (4 percent) of these samples, all from the Winter 1990/91 sampling, at concentrations ranging from 0.199 to 4.42 $\mu g/l$. Forty-one of the samples were collected during the Winter 1990/91 sampling. Figure 4.17 shows Winter 1990/91 DBCP detections within the confined flow system. All three (7 percent) DBCP detections were in previously sampled wells, one offpost and two onpost. DBCP was not detected in any of these wells during the Fall 1989 sampling. The deepest detection of DBCP was from offpost well 37372 at a depth of 88.5 feet below ground surface.

4.2.2.3 Chloroform

Analyses for chloroform were performed on 112 samples collected from the confined flow system during the 1991 water monitoring year. Chloroform was reported in 16 (14 percent) of these samples at concentrations ranging from 0.585 to 97.0 µg/l. The majority of these samples (69) were collected during Winter 1990/91. Chloroform was reported in 11 (16 percent) of these samples at concentrations ranging from 0.585 to 70.1 µg/l. Figure 4.16 shows Winter 1990/91 chloroform detections within the confined flow system. The Winter 1990/91 distribution of chloroform is similar to the Fall 1989 distribution. In a Denver Formation zone 2 well located in Section 23, chloroform was not detected above the CRL in Fall 1989 but a detection of 17.4 µg/l in Winter 1990/91 was reported. The maximum reported depth of chloroform in the Denver Formation is 131.5 feet below ground surface.

4.2.2.4 Dieldrin

Analyses for dieldrin were performed on 85 samples collected from the confined flow system during the 1991 water monitoring year. Dieldrin was reported in nine (11 percent) of these samples at concentrations ranging from 0.499 to 0.982 µg/l. The majority of the samples (44) were collected during Winter 1990/91. Dieldrin was reported in two (5 percent) of these samples at concentrations ranging from 0.499 to 0.982 µg/l. Figure 4.15 shows Winter 1990/91 dieldrin detections within the confined flow system. Both Winter 1990/91 detections were in Section 23 from wells completed in Denver Formation zone 2, and the maximum depth of dieldrin was 70.0 feet below ground surface. These detections are similar to detected values at these locations during the Fall 1989 sampling.

4.2.2.5 Fluoride

Analyses for fluoride were performed on 87 groundwater samples collected from the confined flow system during the 1991 water monitoring year. Fluoride was reported in 71 (82 percent) of these samples at concentrations ranging from 955 to 7600 μg/l. Forty-three of the samples from the confined flow system for fluoride were collected during Winter 1990/91. Fluoride was reported in 40 (93 percent) of these samples at concentrations ranging from 1000 to 7300 μg/l. Figure 4.19 shows Winter 1990/91 fluoride detections within the confined flow system.

Fluoride is a naturally occurring constituent of groundwater. As mentioned in Section 4.2.1.5, the background concentration for fluoride is approximately 1390 μg/l. All Denver Formation zones that were sampled indicate concentrations above 1390 μg/l. Historical CMP confined flow system fluoride data show no significant differences from the 1991 water monitoring year results.

4.2.3 Tentatively Identified Compound Analytical Results

As part of the RMA CMP QA program, GC/MS results are reviewed to assess the presence of nontarget analytes and to tentatively identify these compounds whenever possible. If such compounds are positively identified and repeatedly detected, they will be considered for inclusion on the Army's CMP target analyte list.

Tentatively identified compounds (TICs) were identified on spectra from GC/MS analyses completed during the Spring 1991 monitoring event when an unknown mass spectrum was judged to match the library spectrum with a confidence of 85 percent or better. The occurrence of TICs in the Spring 1991 sampling round is predominantly associated with monitoring wells in Section 26, to the north and northeast of Basins C and F. These TICs and the estimated abundance and frequency of detection of each were recorded to help guide future sampling and analytical activities at RMA. The TIC data for all of the samples analyzed during the Spring 1991 sampling round are summarized in Table 4.6 and provided in Appendix C. The concentration ranges reported for the TICs are estimated because standards, required to properly identify and quantify target compound concentrations, were not analyzed for these compounds.

The TICs in Table 4.6 have been classified into two distinct groups of compounds: (1) CMP target analytes that were not identified during routine GC or GC/MS analyses and (2) non-CMP target analytes. CMP target analytes not identified during the routine GC or GC/MS analysis may not have been originally identified as target analytes because of retention time shifts, matrix interferences, or other sample-specific analytical problems. Methylisobutyl ketone (MIBK) and tetrachloroethene (TCLEE) are the two TICs of this type listed in Table 4.6 with one detection each.

The remaining compounds in Table 4.6 are non-CMP target analytes that are chemically associated with the organosulfur CMP target analytes. Alteration of their original composition may have resulted from environmental conditions at RMA. As noted in Table 4.6, 1-chloro-4-(methylsulfonyl)-benzene was the most often detected TIC in this group.

Because the frequencies and approximate concentrations of the TICs reported for the 1991 water monitoring year are low, no further action is required.

4.2.4 Quality Assurance and Quality Control Data

The QA/QC plan implemented during the CMP is based on the CMP Draft Final Technical Plan Addendum (Stollar and others, 1989b), the CMP Quality Assurance Plan (Stollar and others, 1988), the RMA CQAP (PMRMA, 1989), the requirements of the CMP contract (PMRMA, 1987), and the QA programs of the subcontract laboratories. The objectives of the QA/QC plan are as follows:

- Ensure that technically defensible and consistent field procedures and documentation are used in the collection of samples.
- Assess data accuracy, precision, and representativeness by collecting additional ground-water samples and performing confirmatory analyses.
- Ensure the quality of reported results by performing chemical analyses of all samples, including those collected for QC, according to documented certified method protocols.

The CMP QA/QC plan identifies the required frequency and types of field QC samples that must be collected. These include field, rinse, and trip blanks, duplicate (split) samples, and GC/MS confirmation samples. Field sampling procedures for QC samples are the same as those used for investigative samples, including sample collection, handling, storage, preservation, documentation, and shipping procedures. The CMP Draft Final Technical Plan Addendum (Stollar and others, 1989b) requires that the number of field, rinse, and trip blanks collected in any sampling event must amount to 15 percent of the total groundwater samples collected (5 percent for each type of blank) and stipulates that duplicates must be collected at 10 percent of the wells sampled in any sampling round.

A total of 392 investigative groundwater samples was collected during the 1991 water monitoring year. In addition to the investigative samples, 20 rinse blanks, 20 field blanks, 20 trip blanks, 48 duplicate samples, and 12 GC/MS samples were collected. This section presents a summary and interpretation of the analytical data generated from these field-derived QC samples.

Field blanks are sample bottles filled with distilled water where the investigative sample is collected. Field blanks are submitted for laboratory analysis for the entire target analyte suite to evaluate whether the sampling procedures or conditions at the site have introduced contaminant artifacts into the investigative samples. Contamination in a field blank relates directly to the sampling conditions at the site of the specified well.

Rinse blanks are samples of distilled water decanted from decontaminated field sampling equipment. Rinse blanks are submitted to the laboratory for analysis of the entire analytical suite. Laboratory analyses of rinse blanks measure the effectiveness of field decontamination procedures and also indicate whether sampling techniques compromise the integrity of the investigative samples. Contamination in a rinse blank most directly impacts the sample collected immediately after the rinse blank.

Trip blanks are sample bottles filled by the program laboratory with deionized, organic-free water. These bottles are transported, unopened, to the field site and returned with the investigative samples to the laboratory. Trip blanks are typically analyzed for volatile organic compounds only; however, during the 1991 water monitoring year, trip blanks were analyzed for the entire target analyte list. Analyses of trip blanks reveal whether contaminants may have been introduced during transport and handling. In combination with laboratory QC data, trip blanks may also indicate sources of contamination at the program laboratory.

Duplicate samples submitted to the laboratory for identical analyses are defined under the CMP as two identical sets of sample bottles containing groundwater samples collected from the same location at the same time. Duplicates are collected by alternately filling pairs of identical sample bottles with water from the sampled well. Duplicate samples are analyzed for the entire analytical suite. The analyses of duplicate samples provide a measure of the data variability inherent in the sampling methods, analytical methods, and laboratory operations. Because of the requirements for data entry into the Installation Restoration Data Management System (IRDMS), duplicate samples were identified to the laboratory; no blind duplicate analyses were performed.

The QA/QC plan requires the collection of additional samples at selected wells for confirmatory GC/MS analyses. The GC/MS methods are used to verify the identity and concentrations of volatile and semivolatile organic analytes detected by GC methods. As such, GC/MS confirmatory analyses reveal the efficacy of the routine GC methods used for organic analyses under the CMP. Additional samples were collected for GC/MS confirmation analysis at approximately 20 percent of the wells sampled during the Spring 1991 sampling round.

Laboratory QC data were generated according to the QA/QC plan during the 1991 water monitoring year, and these data were reported weekly to PMRMA in a QA Status Report that included precision and accuracy control charts for each sample lot. QC data were examined by the PMRMA Laboratory Support Division (LSD) in relation to the criteria established during the analytical certification process. Deviations from the established QC criteria were identified by the laboratory to allow appropriate corrective actions. The data were then reviewed for reliability by the program QA officer. Any data deemed unacceptable by PMRMA LSD QA personnel were not accepted for entry into the IRDMS. This process strictly concerns the laboratory aspects of the QA/QC plan, and samples not passing these checks are not elevated for entry into the IRDMS and are thus not reported here. Timing of the various aspects of this report required the use of data that have not been finalized to include all of the Fall 1991 sampling round data. Table 4.7

summarizes the results that were rejected from the RMA database for the Winter 1990/91 and Spring 1991 sampling rounds. Systemic problems for the Winter 1990/91 sampling round were observed for organochlorine pesticides (KK8), dibromochloropropane (AY8), and anions (TT09), where approximately one third of the data were rejected. Problems were also observed in cyanide (TF34), where 20 percent of the data were rejected. The Spring 1991 sampling round exhibited method control problems with hexachlorocyclopentadiene, benzathiazole, and dimethyldisulfide. These data are maintained in the rejected section of the RMA database by the PMRMA database management contractor and are therefore accessible. The CMP laboratory QA/QC program is not discussed further in this report.

4.2.4.1 Evaluation of Field Quality Control Blank Data

There are no strict U.S. Environmental Protection Agency (EPA) or PMRMA published regulatory guidelines for the assessment of field QC blank results or for application of these results in evaluating the technical utility of investigative sample results. For the purposes of this report, the blank data were assessed to identify and, where possible, estimate the magnitude of contamination introduced during sampling, shipping, and analysis. Contamination detected in the field QC blanks was not used to correct or qualify investigative data, but was used to evaluate whether the analytes detected in the investigative samples accurately reflect groundwater quality at RMA. Contaminants identified in the field-generated QC blanks that were absent in the laboratory QC blanks may indicate a potential field sampling problem, a deficiency in bottle preparation, a decontamination problem, or a failure to prepare the laboratory blank in a manner similar to the field blank. A discussion of blank data for volatile organic compounds, semivolatile organic compounds and pesticides, and trace inorganic constituents is presented in the following sections.

Volatile Organic Compounds Blank Data

Five volatile organic compounds (chloroform [CHCL3], chlorobenzene [CLC6H5], dibromo-chloropropane [DBCP], tetrachloroethene [TCLEE], and methylene chloride [CH2CL2]) were identified in field-generated QC blanks during the 1991 water monitoring year. Target analytes were detected above the CRL in three field blanks and four rinse blanks. No trip blank contamination was observed. Table 4.8 lists the sampling round, identity, and concentration of each blank artifact, along with the concentration of the compound in the associated investigative sample. The most common volatile organic compound reported in field-generated QC blanks was CHCL3.

The reported results for CHCL3 in the investigative sample collected from well 33078 may have been impacted by the elevated level of CHCL3 detected in the investigative sample collected from well 33077. This is evidenced by the similar concentrations of CHCL3 in the rinse blank and the subsequent investigative sample (33078). In general, if the concentration of a contaminant in the investigative sample collected after the rinse blank is similar to the concentration of the same constituent detected in the investigative sample collected before the rinse blank, then the decontamination procedures may have impacted the results of the second investigative sample. Similarly, the presence of TCLEE in the rinse blank collected after the sample from well 26157 during the Fall 1991 sampling round indicates that the results reported for TCLEE in well 26171 have also been potentially impacted by ineffective decontamination procedures. The other reported rinse blank contamination for the Winter 1990/91 sampling round does not appear to have impacted the investigative wells sampled after the rinse was collected.

Concentrations of CHCL3, CLC6H5, and TCLEE are reported in the field blanks. However, these contaminants were not detected in the associated investigative samples. A field blank associated with well 33077 contained CLC6H5 at approximately the same concentration as the rinse blank collected at this well. Because Deep Rock distilled water is used to create the rinse and field blanks, this water may be a source of volatile organic compounds in rinse and field blanks. Deep Rock continuously monitors its water for conductance; however, analyses for organic constituents are performed only every four months. In the future, an effort will be made to collect samples of Deep Rock distilled water (or whatever water is used for decontamination) for analyses of all target analytes.

In general, volatile organic compound contamination affected approximately 20 percent of the rinse blanks and 15 percent of the field blanks collected during the 1991 water monitoring year. The relative infrequency of artifact occurrence and the low concentrations detected indicate that the 1991 water monitoring year volatile organic compound data have generally not been compromised by contamination introduced as a result of field or laboratory practices.

Semivolatile Organic Compounds and Pesticides Blank Data

Seven of the 60 field QC blanks collected during the 1991 water monitoring year were contaminated with semivolatile organic compounds and/or pesticides. Artifacts of six target analytes were detected in these blanks, as summarized in Table 4.9.

Two trip blanks collected during the Winter 1990/91 sampling round contained DIMP and aldrin (ALDRN). Because DIMP and ALDRN are not volatile organic compounds, trip blank contamination is due to either handling procedures, laboratory contamination, or instrument memory effects.

Based on a review conducted in a manner consistent with that used to evaluate volatile organic compound results, rinse blank data presented in Table 4.9 indicate that results for well 26075 may have been impacted by ineffective decontamination procedures.

The investigative sample results for well 26086 may have been impacted by contaminants at the surface in air or dust at the sampling site, as shown by the field blank artifacts in Table 4.9. Three field blanks collected during the Winter 1990/91 sampling round contained low concentrations of organochlorine pesticides.

A relatively small number of problems related to QC samples were noted relative to the large number of samples collected and analyzed in the 1991 water monitoring year. The impact on the reported analytical results of the presence of field QC blank artifacts appears to be small and the overall utility of field and laboratory procedures is adequate to maintain the representativeness of the data collected. Therefore, the data are generally considered to be of high technical utility.

Trace Inorganic Constituents Blank Data

Review of inorganic field QC data was confined to trace metals and fluoride because of their potential toxicity and/or association with past RMA operations. Dissolved sodium, potassium, calcium, magnesium, chloride, sulfate, and nitrate were not evaluated because of their natural occurrence in groundwater and the water used to prepare QC blanks. This natural occurrence in both waters complicates the review of the impact QC data may have.

Six inorganic constituents (mercury, arsenic, fluoride, zinc, copper, and chromium) were detected in field-generated QC blanks during the 1991 groundwater monitoring year. These inorganic constituents were present in 23 of the 60 QC blanks analyzed. The inorganic analytes detected in these 23 blanks are summarized in Table 4.10 along with the corresponding analyte concentrations detected in the related investigative samples. Zinc and copper were detected in the rinse blank associated with well 33077. The rinse blank results appear twice in Table 4.10 for this sample because it was analyzed twice, in two separate analytical lots.

The most common inorganic artifact identified in the 1991 water monitoring year blank analyses was mercury, which was detected in the field and rinse blanks collected at six wells. One rinse blank detection of mercury (for well 37353) was reported in the Winter 1990/91 event without a corresponding field blank detection above the CRL. Mercury was detected in a total of five trip blanks. The method blanks for the mercury lots analyzed during the Winter 1990/91 and Spring 1991 sampling rounds showed no contamination. Because the trip blanks used for these sampling rounds were prepared by the laboratory, the noted mercury detections in trip, rinse, and field blanks handling and laboratory procedures are highly suspect. Mercury contamination problems have been noted in the past at the laboratory.

Potential sources of the QC blank contamination may be the trace inorganic constituent present in water used to prepare these blanks. Deep Rock distilled water is used to prepare field blanks for metals analyses. However, because the metals content of this water is not known, conclusions concerning the impact of field procedures on investigative sample results are tenuous.

It is recommended that distilled and deionized water with a known metals content be used to prepare QC blanks.

Summary of Field Quality Control Blank Results

A total of 49 target analytes were detected above the CRL in 30 of the field-generated QC blanks collected for the 1991 water monitoring year. The source of contamination for many of these, whether field or laboratory, cannot be determined from the available data. Although the noted contamination is of concern, the observed contamination does not severely impact the overall usefulness of the reported investigative sample results.

4.2.4.2 Evaluation of Data for Sample Duplicates

The objectives of evaluating field duplicate sample results are to evaluate and quantitate the precision of the reported analytical results and to identify any potential problems in the sampling and analytical processes that could impact the technical utility of the data. Ten percent of the wells in the CMP network were selected at random for duplicate sample collection and analysis.

Duplicate samples were collected from 48 wells during the 1991 water monitoring year. To evaluate the large quantity of paired analytical results, duplicate sample results were summarized statistically using the standard EPA relative percent difference (RPD) calculation (EPA, 1990). Paired analytical results used in this statistical assessment included only those duplicate analyses for which positive identifications were recorded in both the investigative and duplicate samples. The RPD value was not calculated in instances where the investigative sample result is a detection and the duplicate result is not, or visa versa. The RPD for each detection pair was calculated by the following equation:

$$RPD = \frac{|x_1 - x_2|}{\frac{(x_1 + x_2)}{2}} \times 100\%$$

where:

x_1 = concentration of the investigative sample

x_2 = concentration of the duplicate sample

The RPD value for a matched pair of results is expressed as the percent difference that a duplicate result deviates from the average of the two measured concentrations; for example, a RPD value of 67 percent represents a reported concentration that is a factor of two different than that of the duplicate. In general, RPD values are meant to provide a general quantitative indication of analytical precision.

Table 4.11 shows the range of RPDs and the average RPD value for each target analyte detected in the duplicate samples, along with the number of matched pairs utilized in performing the statistical evaluation. The table includes only those analytes for which at least two matched detection pairs were observed; single matched pairs were not sufficient to portray method reliability for a given analyte. Actions taken as a result of duplicate sample analyses must be weighed carefully. It is difficult to determine whether poor precision is a result of sample heterogeneity, sampling variability, method instability, or laboratory sample preparation techniques. Aqueous samples containing high levels of solids or organics, for example, may represent a potential source of erratic duplicate sample results. In general, the results of duplicate sample analyses should be used in combination with other QC sample results to draw conclusions about data quality rather than as a sole basis for such conclusions.

A discussion of duplicate results for volatile organic compounds, semivolatile organic compounds and pesticides, and trace inorganic compounds is presented in the following sections.

Volatile Organic Compounds Duplicate Results

In the 48 sample duplicates analyzed for volatile organic compounds, 72 positive identification pairs were compared to assess the statistical reproducibility of the analytical results. As shown in Table 4.11, volatile organic compound RPD values ranged from zero to 183 percent, with both extremes observed for chloroform.

Also shown in Table 4.11 are the geometric means of the RPD values, which were calculated to minimize outlier bias in the interpretation of method precision for each analyte. For the volatile organic compounds, these values ranged from 0.4 percent, observed for

1,1,1-trichloroethane (111TCE), to 28 percent, which was observed for chlorobenzene. Historical RPD values calculated from EPA data quality objectives (DQOs) for GC methods (based on SW-846 methods) range from 2.8 to 35.5 percent for volatile aromatic compounds and from 13.3 to 39.2 percent for volatile halogenated organics (EPA, 1987). The geometric mean of the average RPD values for volatiles, also shown in Table 4.11, was approximately 6 percent. These results indicate that duplicate results for volatile organic analytes deviated on average by a factor of 1.1 from the original sample result and that average deviations never exceeded a factor of two. This indicates that the precision achieved for volatile organic compounds was generally good. Although isolated cases were observed where RPDs were high, they do not indicate a consistent problem with volatile organic compound analyses.

Semivolatile Organic Compounds and Pesticides Duplicate Results

Statistics for 122 pairs of semivolatile organic compounds and pesticide detections are also presented in Table 4.11. Semivolatile organic compound RPD values ranged from 0 to 170 percent. The highest RPD value was calculated for 2,2-bis(para-chlorophenyl)-1,1,1-trichloroethane (PPDDT). Historical RPDs calculated from the EPA DQOs range from 1.8 to 9.2 percent for organochlorine pesticides and from 7.5 to 28.1 percent for nitrogen-phosphorus pesticides (EPA, 1987).

The geometric mean RPD value calculated for duplicate analyses for all semivolatile organic compounds and pesticides was approximately 18 percent. Therefore, semivolatile organic compounds and pesticides duplicate results were on average confirmed within a factor of 1.2 of the investigative sample results. However, RPD results for individual compounds indicate that the precision of organochlorine pesticide and phosphonate compound analyses may be somewhat less reliable than other semivolatile organic compound analyses, with three compounds showing RPD values indicating duplicate sample variability by a factor of two (vapona and endrin) to nearly four (PPDDT).

Trace Inorganic Compounds Duplicate Results

Duplicate data for 325 pairs of trace inorganic target analyte detections were evaluated, and the resulting statistics are presented in Table 4.11. Inorganic RPD values ranged from 0 to 190 percent (for nitrate) in the 1991 water monitoring year.

The geometric mean of the average RPD values for the inorganic analytes was approximately 16 percent. Thus, inorganic compound duplicate results were, on average, within a factor of 1.2 of each other. Historical RPD values calculated from the EPA DQOs for trace inorganic analyses range from 0.3 to 31 percent (EPA, 1987). Based on the highest observed average RPD of 47 percent for chromium, the majority of duplicate analyses fell within a factor of two of the associated investigative sample analyses.

Summary of Duplicate Results

For the groundwater samples collected during the 1991 water monitoring year, sampling conditions, procedures, preservation, transport, storage, analysis, data manipulation, and QA reviews may have affected technical utility of the data. Duplicate sample analyses were used in estimating the overall contribution of these factors to data variability. For the 1991 water monitoring year, duplicate analyses revealed that analytical results were generally reproducible to within a factor of two for investigative samples. Results from volatile organic compounds appeared to be the most reliable, and semivolatile organic compounds results appeared to be slightly less reproducible than inorganic results.

4.2.4.3 Gas Chromatography/Mass Spectrometry Confirmation Results

GC/MS analyses were performed on 12 of the groundwater samples collected in Spring 1991 to confirm the analytical results from GC methods. Appendix C (on diskette) contains the analytical results for the GC/MS analyses. The GC/MS analytical methods used in this study for volatile organic compounds (UM21 and UM27) and semivolatile organic compounds (UM25 and UM28) analyses are U.S. Army Toxic and Hazardous Materials Agency (USATHAMA) certified methods conducted by DataChem Laboratories and ESE. These methods are based on EPA Methods 624 and 625, respectively.

Nearly all volatile organic compounds and semivolatile organic compounds that are target analytes are routinely analyzed by GC techniques and are also analyzed by the GC/MS methods used for confirmation purposes. The CMP target analytes, methods, and CRLs used for GC and GC/MS analyses are listed in Tables 3.2 and 3.3. The CRLs for GC/MS methods are generally higher than the typical GC methods; therefore, low concentrations cannot always be confirmed by GC/MS analyses. In all cases, if a dilution was required for analysis, the dilution factor was considered when evaluating the reported detection thresholds of sample results. Using the historical guidelines of previous RMA RI/FS investigations, analyses performed during the 1991 water monitoring year were considered confirmed if the GC and GC/MS concentrations were within one order of magnitude of each other.

Confirmation of Volatile Organic Compounds Analyte Results

The 12 Spring 1991 well samples analyzed by both GC and GC/MS reported 16 GC/MS detections for volatile analytes. Eleven of these 16 detection pairs were confirmed within one order of magnitude. GC/MS analyses for five samples detected volatile organic compounds with no similar GC detection reported, even though the GC method had a lower CRL. Therefore, no conclusions may be made regarding the confirmation of the results. One GC result is more than one order of magnitude greater than the GC/MS method CRL and so represents a case of nonconfirmation. The final two detections occurred with GC results requiring dilutions; therefore, the GC CRL was elevated. For the volatile organics analyses for which positive confirmation conclusions may be drawn, 92 percent of the pairs of analytes reviewed are considered confirmed because the reported results are within an order of magnitude.

Confirmation of Semivolatile Organic Compounds Analyte Results

Thirty-five GC/MS detections were recorded for the semivolatile organic compound analytes. Thirteen of the 35 GC/MS detections were paired with GC detections with results that were within one order of magnitude. Twelve GC/MS detections were reported as being greater than the maximum certified range for the GC method; therefore, confirmation of the investigative results and the GC/MS results cannot be made. A single GC/MS result was reported at a concentration greater than one order of magnitude above the GC method CRL; therefore, the GC result is not considered confirmed. For the detection pairs for which confirmation conclusions may be drawn, 93 percent are confirmed within an order of magnitude for the semivolatile analyses.

4.2.4.4 Quality Assurance and Quality Control Conclusions

The analytical results for the 1991 water monitoring year as a whole are reliable and of acceptable technical quality. Field QC sample results suggest only minor field and laboratory handling and procedural influences. Duplicate sample analyses have substantiated that the precision of the sampling and analytical procedures are acceptable, although some problems with the precision of semivolatile results were observed. The GC/MS confirmation analyses demonstrated that 93 percent of the results from which conclusions may be drawn are confirmed within an order of magnitude.

4.2.5 Influences on Data Interpretation

The interpretation of the 1991 water monitoring year analytical data was influenced by several variables that probably represent anthropogenic influences, or the ability to interpret contaminant distributions in more detail, rather than changes in the physical environment. These include changes in the monitoring network and various laboratory analyses and reporting variables, as discussed below.

4.2.5.1 Monitoring Network

Although fewer wells were sampled during the 1991 water monitoring year than during the 1990 water monitoring year, the sampled wells addressed project areas with the specific objective of assessing changes in these areas. Twenty-four newly installed alluvial wells, 3 in the BANS and

21 offpost IRA wells, were sampled during the Winter 1990/91 round. In additional, three newly installed confined flow system wells were added to the sampling network.

The newly installed offpost IRA wells provided new information relative to the north and west of the RMA boundary. The following is a list of new wells where detected values in the samples were higher or lower than expected at that location based on the Fall 1989 plume maps:

- Dieldrin was detected above expected levels in one newly installed well in Section 21, west of the NWBS. This value was very similar to an elevated detection in a nearby, previously sampled well, and indicates that the dieldrin plume extends father north than depicted in the Fall 1989 plume map.

- Chloroform was detected above expected levels in nine newly installed wells north and west of the RMA boundary. Levels higher than expected were also detected in several previously sampled wells in the same areas. This may indicate an extension of the plume depicted in the Fall 1989 plume map in the northwest pathway of more than 3000 feet to the north. An extension of the plume in the northern pathway may be indicated, but by less than about 500 feet. Levels in samples from one newly installed well in Section 12 (north of RMA) were lower than expected.

- DBCP was detected above expected levels in samples from one well in Section 11 north of the RMA boundary and in one well in Section 23. Levels in samples from one newly installed well in Section 12 north of the RMA boundary were slightly lower than expected.

- DIMP was detected above expected levels in samples from eight newly installed wells north and west of the RMA boundary. DIMP was detected below expected levels in samples from two wells, one north of the RMA boundary and one at the BANS. These results, if confirmed in the 1992 water monitoring year, will result in some changes to the DIMP plume configurations, primary through extensions in the 10 μg/l contour in the northern offpost pathway.

- Fluoride was detected above expected levels in samples from three wells north and west of the RMA boundary and below expected levels in samples from two wells north of the RMA boundary. Fluoride was also detected above expected levels in samples from two newly installed wells at the BANS.

4.2.5.2 Laboratory Analysis and Reporting

The effect that analytical data reporting has on the interpretation of results is due to the variations encountered in reporting limits. Variation in CRLs are experienced because of two factors: (1) analysis by different laboratories and (2) sample dilution. The variation in CRLs resulting from either of these factors is discussed in the following paragraphs.

Groundwater samples collected during the 1991 water monitoring year were analyzed at two laboratories: DataChem, Salt Lake City, and ESE, Denver. As presented in Section 3.2.4, the

CRL for each analyte differs depending on the methods of analysis. A listing of the CRLs for the five contaminants of concern in this report is provided in Table 4.12. Table 4.12 also specifies the number of detections reported for each analyte between the two CRL values. For example, 78 detections of DIMP were reported in which the concentration value was greater than 0.392 $\mu g/l$ but less than 10.1 $\mu g/l$. This example demonstrates the differences in the reported results depending on the method used for analysis of a particular analyte.

CRLs also vary because of sample dilutions. Sample dilutions are performed when the concentrations of the analytes exceed the linear range of the instrument. Dilutions may also be necessary if the concentration of an analyte is sufficiently elevated that it masks the detection of other analytes. Dieldrin and fluoride are the only two illustrated contaminants that displayed elevated CRLs because of sample dilutions. A listing of the elevated CRLs that resulted from sample dilution, and the number of samples that were reported as less than the corresponding CRL, is provided in Table 4.13. Fluoride analyses performed at ESE, Denver, were most affected by elevated CRLs as a result of sample dilutions. These dilutions were required because of high concentrations of sulfate typically present in RMA groundwater. Approximately 70 percent of the fluoride analyses reported as less than values were reported at elevated CRLs. A number of these analyses had CRLs above the level considered to represent background RMA conditions. Thus, some fluoride concentrations above background could exist that were masked by the elevated CRLs. In general, the review of the distribution of contaminants in the 1991 water monitoring year is complicated by the variations in CRLs.

4.3 SUMMARY

The following summarize the 1991 water monitoring year CMP data. Section 4.3.1 addresses unconfined flow system data, and Section 4.3.2 addresses confined flow system data. Section 4.3.3 presents conclusions regarding the interaction between the confined and unconfined flow systems. The interpretations presented herein are affected by differences in the available data between the 1990 and 1991 water monitoring years. Water-level data are similar for both years. Analytical data available for the 1991 water monitoring year are much more limited than for the 1990 water monitoring year, primarily in the number of wells sampled.

4.3.1 Unconfined Flow System

The configuration of the water table at RMA roughly resembles the configuration of the bedrock surface. The regional slope of the water table is from southeast to northwest, dropping approximately 200 feet across RMA. Locally, the slope is affected by the thickness of alluvium and the location of paleochannels and escarpments. The most pronounced anomaly is the groundwater mound beneath the South Plants area. This mound is approximately 20 to 30 feet higher in elevation than the regional water-table surface and coincides with a mound in the bedrock surface. The water table is affected locally by the physical barriers at the NBS and NWBS and by the operation of the NBS, NWBS, ICS, and BANS.

The general level of the regional water table remained relatively constant from Winter 1990/91 to Spring 1991, with fluctuations generally less than 1 foot. Fluctuations of up to 5 feet occurred southwest of the ICS, along the north side of the Burlington Ditch, and north of the NBS. Between Spring 1991 and Fall 1991, water-table fluctuations of between 6 and 9 feet occurred southwest of the ICS along the north side of the Burlington Ditch, north of the NBS, and in the South Plants area.

Analytical data obtained from the unconfined flow system during the 1991 water monitoring year were, in general, very similar to data from the 1990 water monitoring year. The data indicated that contaminant plumes containing dieldrin, chloroform, DBCP, and DIMP extended offpost to the north and northwest of RMA. Results of samples from newly installed offpost wells indicate that the offpost plumes of chloroform and DIMP may be larger than previously indicated.

4.3.2 Confined Flow System

The general direction of groundwater flow is to the northwest in all six confined flow system zones, which were monitored during the 1991 water monitoring year. Both the bedrock high in the South Plants and the topography in the vicinity of the Basin A neck affect the direction of groundwater flow. These effects appear to become less prominent with depth; however, fewer wells are completed below Denver Formation zone 1 and, thus, less control exists over the potentiometric surface contours. Previous water-level monitoring has demonstrated that the potentiometric surfaces do not vary significantly according to season. Therefore, comparisons were not made between Winter 1990/91 data and other 1991 water monitoring year data. Changes between the 1990 and 1991 water monitoring year were also relatively minor.

In general, analytical data for Spring 1991 were very similar to Fall 1989 data. Samples from few wells had elevated levels of contaminants in Spring 1991, including chloroform at one location and DBCP at three locations. Samples from three newly installed offpost IRA wells also had higher levels of DIMP than expected, based on historical data. This appears to correspond to the elevated levels of DIMP detected in samples from offpost in the unconfined flow system.

4.3.3 Aquifer Interactions

Potentiometric data and analytical results were used to assess aquifer interaction between the unconfined and confined flow systems. Averaged water-level elevations measured during the 1991 water monitoring year and Winter 1990/91 analytical data were analyzed for this assessment. Aquifer interaction occurs in areas where hydrogeologic conditions permit hydraulic communication between the unconfined and confined flow systems. Vertical gradients between the unconfined and confined flow systems are calculated to indicate the direction of potential flow if communication is present. Analytical data can also be used to identify areas of hydraulic communication between the unconfined and confined flow system.

4.3.3.1 Water-level Data Comparisons

Water-level elevations measured between October 1, 1990, and September 30, 1991, were used to identify the areas of RMA where a vertical hydraulic gradient exists between the unconfined and confined flow systems. Water-level data from well clusters (wells within 50 feet of each other) were used in assessing vertical gradients. Vertical gradients were calculated for each time one of the cluster wells was measured. Linear interpolation of water levels was sometimes necessary because the cluster wells were often measured at different times. Vertical gradients were calculated as the difference in head between the unconfined flow system and the confined flow system divided by the difference in elevation of the midpoints of the screen. The direction of the vertical gradient for each quarter of the year and for the whole year was evaluated by counting the number of upward and downward vertical gradients measured during that time. If upward vertical gradients were predominantly measured, the overall vertical gradient was judged to be upward. The magnitude of the vertical gradient was calculated by averaging the individual measurements during a quarter. The yearly average was calculated as the average of the quarterly averages.

The unconfined flow system and stratigraphically adjacent confined water-bearing zones were monitored by 85 well clusters. The wells in these clusters and the vertical gradient measurements are listed in Table 4.14. Locations of the well clusters are shown in Figure 4.20. Downward hydraulic gradients predominate and existed in 65 well clusters on a yearly basis. Upward vertical gradients existed in 28 well clusters during at least one quarter of the 1991 water monitoring year. The range of downward vertical gradients is from 0.001 to 0.58. The range of upward vertical gradients is from 0.001 to 0.19.

The potential for downward movement of groundwater from the unconfined flow system to the confined flow system exists in areas where the water table in the unconfined flow system is higher than the potentiometric surface of the confined flow surface. Likewise, the potential for upward movement from the confined flow system to the unconfined flow system exists in areas where the potentiometric surface of the confined flow system is higher than the water table in the unconfined flow system. The existence of vertical gradients does not necessarily mean that significant groundwater exchange is occurring between the unconfined and confined flow systems. Instead, aquitards between the unconfined and confined flow system impede vertical groundwater flow.

The magnitude and direction of the vertical gradients appear to reflect the degree of confinement between water-bearing zones. Well clusters with small downward vertical gradients were often in subcrop areas, where confining units were thinnest. Small downward vertical gradients were also associated with confining claystone units that were weathered or fractured. The largest downward vertical gradients or upward vertical gradients correspond to clusters where the confining layer was thickest or most competent.

4.3.3.2 Analytical Data Comparisons

Winter 1990/91 data from all confined flow system wells in the vicinity of unconfined flow system plumes were evaluated to compare water quality between the unconfined and confined flow systems. The assessment is limited by the relatively small number of well clusters that exist in these areas.

The occurrence of DIMP, DBCP, dieldrin, chloroform, and fluoride were examined in the confined flow system to indicate possible vertical interaction between the unconfined and confined flow system. These compounds were chosen because they are representative of a range of contaminant mobilities and toxicities at RMA. DIMP, DBCP, dieldrin, and chloroform are not naturally occurring compounds and their presence in the confined flow system may indicate interaction between the unconfined and confined flow systems via vertical migration of contaminated groundwater. Although fluoride is a naturally occurring constituent of groundwater at RMA, elevated detections above background concentrations may also indicate interaction between the unconfined and confined flow systems.

The distributions of DIMP, DBCP, and chloroform in the confined flow system indicates that aquifer interaction between the unconfined and confined flow systems likely occurs in a downward direction, both onpost in areas of unconfined flow system contamination and offpost in the First Creek pathway. Dieldrin was detected in samples from the unconfined flow system only north of the Basin F IRA area. Confined flow system fluoride concentrations above 2000 μg/l occur both within and outside of unconfined flow system plume locations, indicating that background concentrations of fluoride may be higher in the Denver Formation than in the alluvium.

Interpretation of the vertical distribution of contaminants is complicated by the presence of variable lithologies and lateral discontinuities resulting in disparate potential vertical flow throughout RMA. In general, the horizontal component of flow predominates over the vertical component, thus contamination is generally limited in extent and lower in concentration in the confined flow system.

5.0 ASSESSMENT OF 1991 WATER MONITORING YEAR DATA FOR INTERIM RESPONSE ACTION AREAS

Five IRA areas at RMA were previously selected by the Army for accelerated remedial actions because of the potential they represented for contaminant migration to offpost areas or because the IRAs would provide potentially significant beneficial effects on the groundwater flow regime. These areas include the NBS, NWBS, Basin F IRA area, BANS, and ICS. The objective of this section is to assess the hydraulic impact of the IRA activities, including an assessment of groundwater flow and contaminant migration.

Evaluations of groundwater flow in the IRA areas were based on (1) water-level data collected between October 1, 1990, and September 30, 1991, from the CMP and TOD well networks and (2) supplementary MKE data for the same time. TOD data were collected either weekly or monthly, and CMP data were collected for the Winter, Spring, and Fall 1991 quarters. The TOD network is a denser network of wells than the CMP network, and the wells are generally located closer to the NBS and NWBS than are the CMP wells. TOD typically prepares annual assessment reports for the NBS and NWBS. CMP data were supplemented with available TOD and MKE data in IRA areas where they were applicable to this assessment of the IRA areas.

Evaluations of contaminant migration in the IRA areas are based on analytical data for groundwater samples collected from the CMP network during the three sampling events of the 1991 monitoring year. Current analytical data were compared with historical trends for a number of wells through the use of histograms and historical plume distribution maps. Analytical data for the 1991 water monitoring year can be obtained from the RMA database and are also included in Appendixes B and C (on diskette).

The following sections present a detailed discussion of groundwater flow and contaminant migration for the NBS, NWBS, Basin F IRA area, and BANS. Because analytical data were not collected by the Army in the area of the ICS during the 1991 water monitoring year, only a discussion of groundwater flow is presented for this IRA. A brief summary of IRA activities that occurred at each area during the 1991 water monitoring year is also included.

5.1 NORTH BOUNDARY CONTAINMENT/TREATMENT SYSTEM

The NBS consists of a soil-bentonite barrier wall that extends approximately 6740 feet along the northern boundary of RMA. Extraction wells south of the barrier wall pump groundwater to the NBS treatment facility where it is treated using a granular activated carbon treatment system to remove organic contaminants. Recharge trenches north (downgradient) of the barrier wall recharge treated water to the unconfined flow system. Before 1988, recharge wells were used instead of the recharge trenches. Trenches were installed in 1988 and 1990 to provide increased recharge capacity downgradient of the wall to in turn produce a reversal in hydraulic gradient (i.e., reversal of the northerly regional gradient) across the wall. Recharge trenches installed along the western half of the barrier wall became operational in October 1988, and those installed along the eastern half became operational in July 1990. A reversal in hydraulic gradient is an important component of halting downgradient, offsite migration of contaminants to the north of RMA.

During the 1991 water monitoring year, IRA activities at the NBS consisted of continued testing of the five recharge trenches installed along the eastern half of the NBS. In addition, injection rates in the western trenches were varied to help establish and maintain a reversal in hydraulic gradient along the entire NBS barrier wall.

5.1.1 Groundwater Flow

All available water-level data from the 1991 water monitoring year were used in the evaluation of groundwater flow at the NBS, including data from the three CMP sampling rounds, weekly TOD data, and supplemental MKE data. USGS assumed responsibility for collecting weekly data for TOD starting in April 1991. The wells used in this analysis are shown on the NBS well location map in Figure 5.1.

As discussed in Section 2.0, unconfined conditions exist within both the alluvium and the weathered Denver Formation at RMA. In the area of the NBS where Denver Formation zone 2 subcrops, the upper portion of this zone (i.e., weathered portion) is part of the unconfined flow system. The unweathered portions of zone 2, the underlying Denver Formation zone 3, and stratigraphically deeper zones are part of the confined flow system. Because of concern regarding the potential for flow between the unconfined and confined flow systems south of the barrier wall and an associated potential for offsite migration of contaminants beneath the wall, an assessment of the impact of the NBS on groundwater flow must necessarily include evaluations of both the unconfined and confined flow systems in this area. These evaluations were conducted through development and assessment of the following:

- Water-table maps
- Cross sections of unconfined water levels along the NBS barrier
- Three-point plots showing gradient vectors across the NBS barrier for the unconfined flow system
- Hydrographs of water levels for selected confined and unconfined wells

Water-table maps were prepared to evaluate the general impacts of the NBS on the water-table surface. Water-level cross sections and three-point plots were prepared to assess whether a reversal in hydraulic gradient exists within the unconfined flow system across the barrier wall. Groundwater hydrographs of various well pairs and well clusters were prepared to show the lateral gradients within the unconfined and confined flow systems and the vertical gradients between the unconfined and confined flow systems. These data were also used to evaluate short-term deviations from the average conditions and general trends in water levels over the year.

5.1.1.1 Water-Table Maps

CMP data, TOD data, and some supplemental MKE data were used to generate water-table maps for each of the three CMP monitoring events in 1991. The dates during which these data were collected and the respective quarter designations used in this discussion are as follows:

Date	Quarter
January 23 to February 4, 1991	Winter 1990/91
April 1 to April 9, 1991	Spring 1991
September 16 to September 27, 1991	Fall 1991

These maps, presented in Figures 5.2 through 5.4, were constructed using a 2-foot contour interval to show variations in the configuration of the water-table surface that may not be evident on the regional maps. The smaller contour interval allows for a more detailed assessment of the impact of the NBS on the groundwater flow regime in this area. The general effects of the NBS on the water table in this area include the following:

- A local flattening of the water table south of the barrier wall
- A steepening of the water table just north of the barrier wall
- Localized troughs and mounds indicating the effects of extraction wells, recharge wells, or recharge trenches

Seasonal water-level fluctuations in the vicinity of the NBS were generally less than 2 feet among the three monitoring events. All three maps are generally consistent, showing that the water-table north of the barrier is approximately 1 to 2 feet higher than south of the barrier for most of the system. Thus, a reversal in the normal regional gradient to the north was established along most of the barrier wall during the 1991 water monitoring year. However, a reversal did not occur along the eastern 1200 feet of the wall, which was characterized by a gradient to the north (i.e., normal regional gradient). Elsewhere, groundwater mounding was evident locally on the northern side of the wall in the vicinity of recharge trenches.

5.1.1.2 Water-level Cross Sections and Three-point Plots

Cross sections showing the trace of the water table north and south of the barrier wall, as projected onto the plane of the wall, were prepared for the four quarters of the 1991 water monitoring year (Figures 5.5 through 5.8). In addition, 15 sets of three wells each, located both north and south of the barrier wall, were used in three-point problems to calculate vectors showing the direction and magnitude of the lateral component of groundwater flow in the unconfined flow system (Figures 5.9 through 5.12). The water-level elevations used to construct the cross sections and to calculate gradients using the three-point method are averaged values of all water-level data collected at each well during the respective quarters. The periods for which the cross sections and three-point plots were prepared, the data used, and the quarter designations used in the text discussion, are as follows:

Date	Data Used	Quarter
October 1 to December 31, 1990	TOD, supplemental MKE	First
January 1 to March 31, 1991	CMP, TOD, supplemental MKE	Second
April 1 to June 30, 1991	CMP, TOD (USGS), supplemental MKE	Third
July 1 to September 30, 1991	CMP, TOD (USGS), supplemental MKE	Fourth

The cross sections and three-point problems were based on all water-level data collected between the dates specified, whereas the water-table maps were based on data collected only during the CMP monitoring dates specified. Therefore, direct comparison between these interpretive tools is not possible.

Both the cross section (Figure 5.5) and the three-point plot (Figure 5.9) show that a reversal in hydraulic gradient existed in the unconfined flow system along most of the NBS during the first quarter. This reversal is indicated on the water-level cross sections by the shaded areas in each of these figures. An exception to the reversed gradient is evident along the eastern 1200 feet of the wall, as also noted on the water-table map. Lateral hydraulic gradients across the barrier wall were generally to the south and southeast and ranged from less than 0.010 to 0.053 (Figure 5.9). A northward gradient of up to 0.12 was observed along the eastern portion of the wall.

As can be seen in Figure 5.5, areas of potential nonreversal during the first quarter are evident in the vicinity of well 23527, at the bend in the wall, and in the vicinity of well 23510. However, because only a limited number of data points are available south of the barrier wall, it was necessary to extrapolate the potentiometric surface south of the barrier wall over much longer distances than was required north of the wall. For example, the potentiometric surface south of the wall at the location of well 23510 was extrapolated over a distance of approximately 700 feet. Therefore, a precise understanding of the lateral gradients in the unconfined flow system in these areas cannot be achieved. In the area of well 23510, the three-point plot indicates a southward gradient of 0.025, in contrast to the interpretation suggested from the water-level cross section. Without additional water-level data in these areas, the discrepancy in the conclusions reached using the two interpretive tools cannot be resolved. Along the eastern 1200 feet of the barrier wall, a northward (normal regional) gradient ranging from 0.060 to 0.122 was indicated.

During the second quarter, conditions were very similar to first quarter conditions. As shown in Figure 5.6, a reversal in hydraulic gradient was interpreted to exist along most of the barrier wall, except for the eastern 1200 feet and in the vicinity of wells 23215, 23527, 23510, and 24506. In contrast to the interpretation suggested from the cross section, however, the three-point plot indicates a southern gradient of 0.022 in the area of well 23510 and a gradient of 0.006 in the area of well 24506. As previously discussed, this discrepancy may be a result of the lack of water-level data used for the cross section south of the barrier wall in these areas. The three-point plot is consistent with the water-level cross section in the area of well 23215, showing a northern gradient of 0.012. Along the eastern 1200 feet of the barrier wall, a northward gradient ranging from 0.060 to 0.121 was again interpreted.

During the third quarter, a reversal in hydraulic gradient existed along the entire length of the barrier wall, except near well 23527, at the bend, and along the eastern 1200 feet. Based on the three-point plots, the lateral gradients were consistently to the south and consistently higher than in the first and second quarters, ranging from 0.011 to 0.087 However, insufficient data were available for the area of well 23527 to calculate a gradient using the three-point method. Along the eastern 1200-foot section of the wall, the northward gradient decreased slightly, ranging from 0.027 to 0.101.

During the fourth quarter, a reversal in gradient existed along the entire length of the wall, except for the eastern 1200-foot portion. Northward gradients along this portion of the wall ranged from 0.044 to 0.088.

5.1.1.3 Groundwater Hydrographs

The NBS was designed to remove and treat contaminated groundwater in the alluvial groundwater system before it migrates offpost. It is the Army's operational goal to maintain a reverse hydraulic gradient in the unconfined and, if possible, in the confined flow system to achieve the goal of halting offpost migration of contaminated alluvial groundwater. To assess flow within and between these systems, groundwater hydrographs were produced to evaluate the following:

- Lateral hydraulic gradients across the barrier wall within the unconfined flow system
- Lateral hydraulic gradients across the barrier wall within the confined flow system
- Vertical hydraulic gradients between the unconfined and confined flow systems, both north and south of the barrier wall

To evaluate the lateral hydraulic gradients across the barrier wall within the unconfined flow system, hydrographs were prepared for pairs of unconfined wells. Five of these provide spatial coverage along the length of the barrier wall and demonstrate hydraulic conditions for the unconfined flow system at the NBS (Figures 5.13 through 5.17). Each of these hydrographs shows water-level data for two wells close to one another, one north and one south of the barrier wall. In general, they all show a consistent reversal in hydraulic gradient occurring after April 1, 1991, consistent with the gradient vectors calculated using the three-point method. Thus, system operations maintained a reversal in hydraulic gradient along this portion of the wall after the second quarter of the 1991 water monitoring year.

To evaluate the lateral hydraulic gradients within the confined flow system near the NBS, groundwater hydrographs were prepared for three pairs of confined wells (Figures 5.18 through 5.20). Each of these hydrographs shows water-level data for two wells, one north and one south of the barrier wall. These wells are generally close to one another, except for wells 23161 and 23234, which are 750 feet apart. One well pair is in Section 23 and two are in Section 24. The hydrograph from Section 23 (Figure 5.18) shows that a normal regional gradient (i.e., to the north) existed within the confined Denver Formation zone 3 in this area during the 1991 water monitoring year. Data from the two well pairs in Section 24 (Figures 5.19 and 5.20) show that a normal regional gradient existed within the confined Denver Formation zone 3 during most of the 1991 water monitoring year, and a reversal in hydraulic gradient occurred during September 1991.

However, the hydraulic head at well 24204, north of the wall, was only 0.1 foot higher than the head at well 24205, south of the wall. This small difference indicates that the reversal in hydraulic gradient in this area is slight, at best, and may change as a result of normal fluctuations in the data.

To evaluate the vertical hydraulic gradients between the confined and unconfined flow systems, groundwater hydrographs were prepared for six well clusters that provide spatial coverage along the length of the barrier wall and show the observed range of conditions (Figures 5.21 through 5.26). Three of these clusters are north of the wall and three are south of the wall, as shown in Figure 5.1. A well cluster is defined as a set of wells completed at different depth intervals within the confined and unconfined flow systems and that are close to one another. For evaluating vertical gradients at the NBS, cluster wells averaged approximately 50 feet from one another and the maximum distance was approximately 200 feet. Larger distances between cluster wells were used for the NWBS because there are fewer wells with sufficient water-level data. As discussed in Section 5.1.1, the unconfined flow system at the NBS consists of the alluvium and the weathered portions of Denver Formation zone 2. The confined flow system consists of the unweathered portion of Denver Formation zone 2, the underlying Denver Formation zone 3, and stratigraphically deeper zones. Table 5.1 summarizes the observations regarding the direction of vertical gradients at these cluster locations.

The three hydrographs of well clusters north of the barrier wall (Figures 5.21 through 5.23) show that, except for very early in October 1990, hydraulic heads in the unconfined flow system were consistently higher than heads in the underlying confined Denver zones 2, 3, and 5. Figure 5.21 also shows that there was an upward gradient from Denver Formation zone 5 to Denver Formation zone 2 at this location.

The hydrograph of the one well cluster south of the wall in Section 23 (Figure 5.24) indicates that heads in the unconfined flow system were very similar to the heads in two adjacent wells that are screened in confined Denver zone 2. This suggests that there is hydraulic connection between the unconfined flow system and the confined Denver Formation zone 2 wells in this area. It may also indicate that the Denver Formation zone 2 may be unconfined in this area. However, during September 1991, the heads in the unconfined flow system and confined flow system at this location showed separation and an upward gradient from the confined Denver Formation zone 2 to the unconfined system. The two hydrographs of well clusters south of the wall in Section 24 (Figures 5.25 and 5.26) show that, during the second and third quarters, heads in the unconfined flow system were higher than heads in confined Denver Formation zone 3 wells. However, data collected during September 1991 indicate that heads in the confined Denver Formation zone 3 wells were slightly higher than heads in the unconfined flow system, indicating an upward gradient from the confined to the unconfined system. This upward gradient is favorable in that it helps to preclude the downward migration of contaminants from the unconfined flow system to the confined flow system upgradient of the barrier wall that could then flow offsite via the confined flow system.

5.1.1.4 Summary

In general, the water-level data demonstrate that a reversal in hydraulic gradient was established in the unconfined flow system at the NBS during the 1991 water monitoring year. The exception to this reversal was observed along the eastern 1200 feet of the barrier wall, where a normal hydraulic gradient (i.e., to the north) was present throughout the 1991 water monitoring year. The reversal in gradient was not maintained for short periods at a number of locations along the barrier wall because of decreases in injection or extraction rates, or increased precipitation. One area of particular concern is at the bend in the wall; data for this area suggest that long-term reversal has not been achieved. However, additional data are necessary to adequately assess groundwater flow conditions in this local area.

Within the confined flow system at the NBS, water-level data indicate that a reversal in the lateral hydraulic gradient was not present throughout most of the 1991 water monitoring year. However, data collected during September 1991 indicate that a reversal in gradient was present at that time along a portion of the wall in Section 24. This change may be a result of increased heads within the confined flow system north of the barrier wall as a result of operation of the recharge trenches within the unconfined flow system.

Vertical gradients between the unconfined and confined flow system north of the barrier wall were consistently downward during the 1991 water monitoring year. South of the wall, data also indicate a downward gradient throughout most of 1991. However, an upward gradient was evident at the time of measurement during the fourth quarter.

5.1.2 Contaminant Migration

Contaminant migration was assessed at the NBS for both the unconfined and flow systems through the use of contaminant distribution maps and water quality histograms. Sections 5.1.2.1 and 5.1.2.2 present discussions of contaminant migration in the unconfined and confined flow systems, respectively.

5.1.2.1 Unconfined Flow System

Contaminant migration and temporal trends for the unconfined flow system at the NBS were evaluated through the use of contaminant distribution maps and histograms for DIMP, DBCP, dieldrin, chloroform, and fluoride. The contaminant distribution maps were used to assess changes in the areal extent of the contaminants. The histograms were used to assess increases or decreases in concentrations that could be related to the effectiveness of the NBS in preventing the offsite migration of contaminants.

Figures 4.10 through 4.14 present contaminant distribution maps for DIMP, DBCP, dieldrin, chloroform, and fluoride, respectively, in the unconfined flow system. These maps show the 1989/90 plumes for the respective parameters (Stollar and others, 1991) with the detections for the Winter 1990/91 sampling round superimposed. By evaluating these detections with respect to the 1989/90 plume configuration, it is possible to assess changes in the areal distribution of contaminants within the unconfined flow system that may have occurred since the 1990 water monitoring year.

Figures 5.27 through 5.31 present histograms of contaminant concentrations over time for selected wells screened in the unconfined flow system at the NBS. The selected wells were chosen on the basis of the following criteria:

- They were part of the CMP network.
- They provide an adequate areal distribution of data in the area of the NBS.
- They had long-term historical data.
- They were wells of potential concern (i.e., those having high concentrations historically).

The areal distribution map for DIMP (Figure 4.14) is basically the same in the area of the NBS, except that DIMP was detected in samples from several wells outside of the 10.0 μg/l isoconcentration contour at the eastern end of the wall at concentrations greater than 10.0 μg/l. Thus, it is interpreted that the 10.0 μg/l portion of the plume has extended to the east since the 1990 water monitoring year. The distribution of detections greater than 10.0 μg/l along the northern pathway would extend the plume farther east and farther north into Sections 2 and 11. However, the wells for which these detections were reported were not sampled during the 1990 water monitoring year. Therefore, the extension of the plume is not necessarily a result of migration, but of an improved understanding of the plume configuration as a result of changes in the sampling network. In addition, as a result of a new well (37429) included in the sampling network in Section 10, there would also be a slight enlargement westward of the plume along the First Creek pathway. Samples from several wells in this plume have shown increases in concentration since the 1990 water monitoring year. The most significant increase, from 15.2 to 160 μg/l, was noted in well 37370. In addition, the reported concentration of DIMP in Section 3 at wells 37356 and 37357 increased slightly during the 1990 water monitoring year.

Figure 5.27 presents histograms of DIMP concentrations since 1978 for 21 wells near the NBS. DIMP concentrations have generally not exhibited a consistent change in concentration south (i.e., upgradient) of the wall since sampling was initiated, except in samples from wells 24127 and 24135. Samples from well 24127 have shown significant increases in concentration since 1985. Samples from well 24135, 500 feet to the east, have shown significant decreases in concentration since 1986. Samples from wells 23085 and 23118, located south of the NBS, have shown slight decreases in concentration since startup of the recharge trenches in October 1988.

Downgradient of the barrier wall, concentrations of DIMP have decreased significantly since recharge trench startup (i.e., from >100 to <10 $\mu g/l$) in samples from wells 23202 and 23204, screened in the unconfined Denver just below the recharge trenches. These decreases are likely a result of dilution because of recharge to the trench. Therefore, they may only be representative of conditions at the recharge trenches, rather than at the NBS as a whole. Samples from wells 23235, 37339, and 23198 also showed decreases in DIMP concentration after startup of the recharge trenches, although not quite as significant. Samples from well 23047 showed significant decreases in concentration levels after 1983. This decrease is most likely related to the NBS extension, which became operational in January 1982. Samples from other wells north of the wall have not changed significantly in reported DIMP concentration over time (i.e., wells 24164, 24166, 37338). The concentration of DIMP is decreasing with time in well 23226.

Figure 4.12 presents a contaminant distribution map for DBCP. In the area of the NBS, DBCP is present primarily along the northern pathway. Sporadic detections occur at low levels along the First Creek pathway; these detections have increased in concentration since the 1990 water monitoring year. The distribution along the northern pathway does not appear to be significantly different from the 1989/90 plume map, except that samples from two wells outside of the plume had detections greater than 0.195 $\mu g/l$ (i.e., the highest CRL) in the 1991 water monitoring year. One of these wells was not sampled in 1990 but samples from the other (well 37389, near the NBS) show a slight increase in concentration since it was last sampled in 1990.

Figure 5.28 presents histograms of DBCP concentrations since 1978 for 19 wells near the NBS. Upgradient of the NBS, DBCP has not recently been reported in samples from wells 23118, 23085, 24184, and 24185. In samples from wells upgradient of the NBS (i.e., 23123, 24135, 24127, and 24101), concentrations have generally declined over time, with only minor fluctuations.

North of the NBS wall, DBCP has only been reported sporadically in recent years. Samples from well 24191 had no detections before 1988, but have shown low levels of DBCP since trench operations began.

Winter 1990/91 detections of dieldrin in the vicinity of the NBS (Figure 4.1) are consistent with the 1990 water monitoring year plumes. An isolated detection of 0.0567 $\mu g/l$ was reported for a sample from along the northern pathway at the boundary of Sections 12 and 13. This well (37320) has shown increased concentrations since last sampled.

Figure 5.29 presents histograms of dieldrin concentrations since 1979 for 21 wells near the NBS. Samples from all of the wells south of the barrier wall, except 23118 and 24184, have shown consistent detections of dieldrin of less than 10 $\mu g/l$ since sampling was initiated. Consistent detections have been reported for well 23118 since 1987, and no detections have been reported for well 24184, near the eastern portion of the NBS. Dieldrin has been detected in samples from several wells north of the NBS (i.e., 23198, 37307, 23204, 24161, and 37312), but at somewhat lower levels than in samples from wells south of the wall (i.e., generally less than 3 $\mu g/l$). Samples from well 23204, screened in the unconfined Denver Formation below a recharge trench, have had no detections since startup of the recharge trenches in 1988. Based on one sampling event (i.e., 1991), well 37307 has had no detections since startup of the additional recharge trenches in 1990. However, dieldrin continues to be detected in well 24161 and well 37312, 300 feet downgradient of the recharge trenches, indicating that dilution is probably responsible for the decreased dieldrin concentrations in the immediate vicinity of the trenches.

The distribution of chloroform (Figure 4.11) was interpreted to be more areally extensive in 1991 than in the 1990 water monitoring year. This is primarily a result of detections in samples from wells that were not sampled during the 1990 water monitoring year. Therefore, it does not necessarily indicate plume migration. In addition, isolated detections were reported for wells farther north in Section 11 and near the South Platte River, in Sections 3 and 34. Concentrations reported for these wells have increased since the 1990 water monitoring year.

Figure 5.30 presents histograms of chloroform concentrations for 17 wells in the vicinity of the NBS. Analyses for chloroform in wells near the NBS were not initiated until 1986. Since that time, chloroform concentrations in samples from upgradient wells 23231 and 24101 have decreased. Concentrations have remained relatively constant in samples from other upgradient wells. A relatively abrupt decrease in concentrations is evident in samples from some wells down-gradient of the wall, coincident with startup of the recharge trenches in October 1988.

The distribution of fluoride during the Winter 1990/91 (Figure 4.14) was interpreted to be basically the same as for the 1990 water monitoring year. The portion of the plume in offpost Sections 9, 10, and 15 appears to be somewhat larger. This is primarily a result of detections higher than 2000 $\mu g/l$ in samples from wells that were not sampled during the 1990 water monitoring year. Therefore, no change in fluoride migration is necessarily indicated.

Figure 5.31 presents histograms of fluoride concentrations since 1978 for 19 wells near the NBS. Concentrations of fluoride show no consistent changes in samples from this area. In addition, concentrations in samples from wells north and south of the barrier are generally equivalent. The NBS was not designed to remove fluoride from groundwater. Therefore, the observed consistency in fluoride levels is expected.

Histograms of temporal variations in contaminant concentration were also prepared for offpost wells in areas downgradient of the NBS. Concentrations of the five contaminants presented for the NBS are shown for wells within the First Creek and northern offpost pathways in Figures 5.32 through 5.36. The purpose of these histograms is to assess the degree of remediation that has occurred as a result of the NBS operations. As shown in Figure 5.32, concentrations of DIMP generally decreased in most wells north of the NBS. Concentrations of DBCP, which are much less areally extensive than DIMP, also appear to have decreased with time. In the First Creek pathway, wells 37381 and 37373, for which no detections were reported before 1991, both had reported detections during the 1991 sampling. As shown in Figure 5.34, changes in dieldrin concentrations north of the NBS are not apparent. Unfortunately, many of the 1991 water monitoring year dieldrin samples collected in this area failed to meet PMRMA QA objectives and were rejected from the database. However, water monitoring year data for 1991 indicate that dieldrin concentrations in samples from wells 37309, 37308, and 37373 have decreased compared to concentrations from previous years. Chloroform histograms (Figure 5.35) north of the NBS indicate both increasing and decreasing trends. Chloroform concentrations appear to be decreasing slightly in wells 37323, 37391, and 37367. Farther north, chloroform concentrations increase in well 37368. Histograms showing fluoride concentrations in wells north of the NBS (Figure 5.36) seem to have remained relatively constant over time.

5.1.2.2 Confined Flow System

Contaminant migration within the confined flow system at the NBS was evaluated through the use of contaminant distribution maps. These maps, presented in Figures 4.15 through 4.19, show detections of DIMP, dieldrin, DBCP, chloroform, and fluoride in samples from the confined flow system for the 1991 water monitoring year. Table 5.2 summarizes contaminant concentrations for both the 1990 and 1991 water monitoring years.

For upgradient wells from which samples were collected during the 1991 water monitoring year, detections of DIMP (Figure 4.18) were reported for only one well (23218, zone 2). Concentrations in samples from this well were generally the same for the last two monitoring years. For all upgradient wells sampled, no detections have been reported above CRLs historically, except for well 23177 (zone 2). The maximum concentration detected in samples from this well was 230 μg/l in 1984, but no detections have been reported during the last two monitoring years. Samples from two upgradient zone 2 wells (24127, 23144) had high concentrations of DIMP during the 1990 water monitoring year. However, these wells were not sampled during the 1991 water monitoring year. The high concentrations of DIMP detected in the 1990 samples from these wells suggested bypass through the confined Denver Formation beneath the barrier wall (GeoTrans, 1991). One of these wells, 24127, is classified as part of the unconfined system. Therefore, high concentrations of DIMP in samples from this well are not indicative of conditions in the confined flow system upgradient of the barrier.

In samples from wells downgradient of the NBS, DIMP was reported in several confined flow systems during the 1991 water monitoring year. In general, these detections were consistent with historical values at these wells.

As indicated in Figure 4.15, dieldrin was not reported in the vicinity of the NBS during the 1991 water monitoring year. DBCP was reported in two wells (24171 and 37372) in the vicinity of the NBS during 1991 (Figure 4.17). Chloroform concentrations were reported in samples from only a few confined wells at the NBS (Figure 4.16) during the 1991 water monitoring year. DBCP and chloroform confined flow system detections were not highly consistent with historical data, and reported values were close to method CRLs.

Detected concentrations of fluoride (Figure 4.19) were generally consistent between the Fall 1989 and Winter 1990/91 sampling events.

5.1.2.3 Summary

Evaluations of contaminant migration and trends at and north of the NBS lead to three general observations. First, the concentrations of mobile contaminants, such as DIMP and chloroform, have decreased significantly in the immediate vicinity of the NBS but are still present in the offpost area, indicating that the primary source of these contaminants has been cut off by the NBS. However, the remnant contamination remains beyond the RMA northern boundary. Second, the less mobile contaminants, represented by dieldrin, appear to have been halted at the NBS, as illustrated by the higher concentrations of dieldrin south of the NBS. Further, dieldrin does not appear to have migrated very far offpost. Reductions in dieldrin concentrations do not appear to have been achieved over time in downgradient wells, except in the immediate vicinity of the trenches where dilution is probably the controlling factor. Third, the fluoride histograms show no apparent impact by the NBS on fluoride, as expected.

The potentiometric data show that reversals in hydraulic gradient are commonly occurring in some portions of the NBS in the unconfined flow system. The reversal in hydraulic gradient was not present throughout the 1991 monitoring year along the eastern 1200 feet of the barrier wall and was less well established at the bend in the wall. The data from the confined flow system indicate a reversed lateral hydraulic gradient was not present throughout most of the 1991 monitoring year. However, a reversal in the confined flow system gradient was present along a portion of the wall in Section 24 during September 1991. Contaminant concentration trends generally indicate that the NBS is effective. However, additional information will be required near the bend in the wall to further evaluate the efficiency of the wall in this area.

5.2 NORTHWEST BOUNDARY CONTAINMENT/TREATMENT SYSTEM

The NWBS was designed to prevent the migration of contaminants, particularly DBCP, offpost to the northwest of RMA. Recent improvements to the NWBS were made primarily because of the presence of dieldrin offpost and northwest of RMA that was apparently bypassing the original system. The original system, which became operational in January 1985, consisted of a soil-bentonite barrier wall, approximately 1425 feet long, and a system of extraction and recharge wells approximately 2300 feet long designed to form both a hydraulic and physical barrier. The hydraulic barrier portion of the system extends 900 feet southwest of the barrier wall and consists of a series of extraction wells spaced 100 feet apart and recharge wells spaced 75 feet apart along the southwest portion of the barrier and 150 feet apart along the northeast portion of the barrier system. Another series of extraction and recharge wells is located on either side of the barrier wall. Groundwater extracted at the NWBS is treated using an activated carbon treatment system to remove organic contaminants and is recharged to the unconfined flow system via recharge wells downgradient of the barrier wall.

The Army and Shell instituted improvements to the NWBS because an alluvial channel had been identified northeast of the original NWBS that would allow bypass of the system. These improvements included a 665-foot-long extension at the northeast end of the barrier wall that was added during 1990 and two new groundwater extraction wells.

The effectiveness of the NWBS was assessed through evaluations of groundwater flow and contaminant migration as presented in Sections 5.2.1 and 5.2.2, respectively.

5.2.1 Groundwater Flow

All available water-level data collected during the 1991 water monitoring year were used in the analysis of groundwater flow at the NWBS. These include data from the three CMP monitoring events, weekly TOD data, and supplemental MKE data. The wells used in this analysis are shown in Figure 5.37.

This assessment of groundwater flow involved the development and evaluation of the following:

- Water-table maps
- Water-level cross sections
- Three-point plots

Water-table maps were prepared to evaluate the general impacts of the NWBS on the water-table surface. Water-level cross sections and three-point plots were prepared to assess whether a reversal in hydraulic gradient exists within the unconfined aquifer across the barrier wall.

Limited data are available for the confined flow system at the NWBS. Only one well cluster in this area includes wells screened in the confined flow system. Water-level data from this cluster, upgradient and near the southwestern end of the NWBS, have shown that a downward vertical gradient exists between the unconfined and confined flow systems at this location (Stollar and others, 1991). Because unconfined-confined aquifer interaction in this area has not been identified as a concern (Stollar and others, 1991), this evaluation primarily concentrated on an assessment of the hydraulic impact of the NWBS on the unconfined flow system.

5.2.1.1 Water-Table Maps

Water-table maps were generated for each of the three CMP monitoring events in the 1991 water monitoring year, as described for the NBS (Section 5.1.1.1). These maps, presented in Figures 5.2 through 5.4, were constructed using a 2-foot contour interval to show the effects of the NWBS on the groundwater flow regime in this area.

During the Winter quarter, the water-table configuration was characterized by a narrow trough trending northwest-southeast across the southwestern portion of the barrier wall. Along the northeastern 1000 feet of the barrier, where an extension was installed in 1990, gradients were steeper and groundwater flow is from northeast to southwest and parallel to the wall at a gradient of approximately 0.026. Groundwater flow is toward the trough at the southwestern end of the wall, suggesting either more efficient recharge (and, hence, less head buildup) in the central portion of the NWBS, or less water being directed toward the central portion of the wall because of NWBS operations.

A general flattening of the water table is apparent southwest of the wall in the area of the hydraulic barrier. In this area, the water-table map suggests a gradient to the north toward the extraction wells. A reversal in hydraulic gradient was not apparent from the water-table map during this quarter.

During the Spring quarter, the water-table configuration was generally similar to that for the Winter quarter, except that small decreases in water-table elevations downgradient of and near the southwestern end of the barrier wall were evident. Thus, the extraction wells appeared to be drawing down the water table at a fairly rapid rate in this area of the NWBS. A reversal in hydraulic gradient was not apparent from the map.

The Fall 1991 water-table configuration, showing conditions five months after the Spring quarter, was significantly different than the first two quarters. The water table in the area of the hydraulic barrier was characterized by a closed low and the water-table elevations north (down-gradient) of the wall rose 4 to 6 feet. The water table showed more of a flattening upgradient of the wall, and heads immediately north of the wall were generally 1 to 2 feet higher than heads south of the wall. Thus, a reversal in hydraulic gradient was established along the majority of the system. The eastern 1000 feet was, again, similar to previous quarters with gradients to the southwest and parallel to the wall but at somewhat lower values (i.e., 0.018).

In summary, the water-table maps indicate that recharge downgradient of the barrier wall was sufficient to produce a small reversal in hydraulic gradient along most of the wall during the

Fall quarter. A reversal was not apparent from the water-table maps along the eastern extension of the wall or southwest of the wall in the area of the hydraulic barrier.

5.2.1.2 Water-level Cross Sections and Three-point Plots

Cross sections showing the trace of the water table both northwest and southeast of the barrier wall, as projected onto the plane of the wall, were prepared for each of the four quarters of the 1991 monitoring year (Figures 5.38 through 5.41). The monitoring periods and data used for these evaluations are the same as those used for the NBS (see Section 5.1.1.2). The water levels southeast of the barrier wall were projected less than 10 feet and those northwest of the barrier wall were projected approximately 350 feet. These projected data were not corrected to account for lateral gradients in this area. The water-level elevations used to construct these cross sections are averaged values of all water-level data collected during the respective quarter for a specific well.

Four sets of wells, both north and south of the NWBS, were used to calculate vectors using three-point problems showing the direction and magnitude of the lateral component of ground-water flow in the unconfined flow system (Figures 5.42 through 5.45). Averaged quarterly water levels were also used in calculating solutions to the three-point problems.

Both the cross sections and the three-point problems show that a reversal in hydraulic gradient (i.e., to the southeast) existed along most of the original portion of the barrier wall and along the hydraulic barrier during the 1991 water monitoring year. The gradients calculated using the three-point method ranged from 0.001 to 0.007 for the first three quarters, increasing to 0.012 at the center of the wall during the fourth quarter. The water-level cross sections indicate that heads northwest of the wall were 1 to 3 feet higher than heads south of the wall during the first and second quarters.

During the third quarter, the head differences were not as great, ranging from 1 to less than 2 feet higher northwest of the system than southeast of the system. However, a significant head difference was evident along the original portion of the barrier wall during the fourth quarter. In this area, heads were approximately 5 feet higher downgradient of the wall. In the area of the hydraulic barrier, gradient reversals as small as 0.001 were reported, indicating that although a reversal has been achieved, an increase in the reversed gradient would provide added assurance regarding the efficiency of the hydraulic barrier. In this area, heads northwest of the system were only 1 foot higher than those southeast of the system. Thus, the establishment of a reversal in hydraulic gradient appears to have been most successful along the original portion of the barrier wall. As noted on the cross section, three-point plots, and water-table maps, a reversal in hydraulic gradient was not achieved along the northeastern portion of the wall where the extension was added during 1990. The gradient in this area was 0.042 to 0.051 to the southwest.

5.2.2 Contaminant Migration

Contaminant migration and temporal trends in the vicinity of the NWBS were assessed by examining recent and historical CMP data from wells screened in the unconfined flow system. These data were evaluated through the use of contaminant distribution maps and contaminant histograms.

Figures 4.10 through 4.14 present contaminant distribution maps of the unconfined flow system for DIMP, dieldrin, DBCP, chloride, and fluoride, respectively. These maps show the Fall 1989 plumes (Stollar and others, 1991) for the respective parameters with the Winter 1990/91 detections superimposed. By evaluating these detections with respect to the Fall 1989 plume configuration, it is possible to assess changes in the areal distribution of contaminants that may have occurred since the 1990 water monitoring year. Figures 5.46 through 5.50 present histograms of contaminant concentrations over time for selected wells screened in the unconfined flow system at the NWBS. The criteria by which the wells were selected are the same as those used at the NBS (as discussed in Section 5.1.2.1).

As shown in Figures 4.10, 4.12, and 4.13, either no changes or only small variations in the distributions of dieldrin, DBCP, and DIMP from that shown for the 1990 water monitoring year were apparent. Minor differences include an isolated high detection of 16.1 μg/l for DIMP in a sample from downgradient of the NWBS in Section 16 at well 37430, and a slight enlargement and northward extension of the dieldrin plume in an area southwest of the barrier system. The detection of 16.1 $\mu g/l$ noted in a sample from a well (37430) was not sampled in the 1990 water monitoring year. The slight northward extension of the dieldrin plume is a result of increases in concentration (i.e., from nondetect to 0.0911 $\mu g/l$) in samples from well 37335 and detections in samples from a well not sampled in the 1990 water monitoring year.

DIMP analytical data, accumulated from 1978 to the present, are graphically displayed as histograms for 21 wells near the NWBS (Figure 5.46). Since about 1987, these histograms generally show only minimal fluctuations in concentrations. Significant declines in DIMP concentrations were noted in samples from well 37332, downgradient of the barrier wall, and wells 27076 and 22008, upgradient of the NWBS.

Historical and recent dieldrin levels are shown for samples from 27 wells in Figure 5.47. Unfortunately, many of the dieldrin analytical results for the Winter 1990/91 sampling event did not pass PMRMA QA guidelines and were rejected from the database. Dieldrin contamination has persisted southeast of the barrier wall since monitoring began in 1978. Concentrations have generally been consistent, except for samples from wells 27064 and 22043, which showed slight increases since monitoring of these wells began in 1986. Concentrations of dieldrin in samples downgradient of the wall have decreased for only two of the wells for which historical data were evaluated (i.e., 37330 and 37331). Dieldrin has not been reported in samples from these wells since 1985. Dieldrin was not reported in samples from well 37333 until 1986, from which time it has been consistently detected at low levels but with decreases in concentration after 1988. Data for samples from wells 27072, 27085, and 37334 indicate the persistence of low levels of dieldrin (less than 2.0 $\mu g/l$) both onpost and offpost to the south and southwest of the NWBS.

Figure 5.48 presents temporal DBCP data for 21 wells near the NWBS. Upgradient of the NWBS, samples from several wells have reported no detections of DBCP since sampling was initiated. Samples from other wells near the southwest end of the system and upgradient of the hydraulic barrier (i.e., 22008, 27076, 27062, and 22053) have reported detections of DBCP as high as 1.0 $\mu g/l$ in previous years. However, no sample from any of these wells has reported a detection since 1988. Samples from other wells upgradient of the barrier have shown only sporadic detections of DBCP. Samples from wells downgradient of the barrier wall have generally either shown no detections or sporadic detections showing no clear trend of DBCP contamination.

Current data from the Winter 1990/91 sampling event indicate a difference in the distribution of chloroform near the NWBS since the 1990 water monitoring year (Figure 4.11). Recent detections were reported for an area extending approximately 7000 feet farther north than the plume shown for the 1990 water monitoring year. In addition, the plume appears areally larger downgradient of the system, and the distribution of chloroform at the southwest end of the NWBS extends slightly farther west. These changes in interpretation are, in part, a result of the addition of new wells to the sampling network, particularly the northward extension of detected chloroform identified through the installation of three new wells in Sections 15 and 16. Chloroform analytical data collected from 1986 to the present are shown as histograms for 15 wells near the NWBS (Figure 5.49). Overall, chloroform concentrations have remained relatively constant on both sides of the NWBS, at levels generally below 50 μg/l. These levels are below the treatment operational criteria for the NWBS IRA of 100 μg/l for total trihalomethanes. The current treatment system at the NWBS is not specifically designed to treat chloroform.

The distribution of fluoride in the vicinity of the NBS decreased slightly downgradient of the NWBS in 1991. Based on the histograms for 23 wells shown in Figure 5.50, fluoride concentrations generally ranged from 1000 to 5000 μg/l in samples from all of the upgradient and downgradient wells monitored, and no clear temporal or spatial variations were apparent. The NWBS was not designed to remove inorganic contaminants and, thus, a contrast in upgradient and downgradient concentrations was not expected.

5.2.3 Summary

In summary, concentrations of DIMP and DBCP downgradient of the NWBS have not changed significantly either temporally or spatially in the area of the NWBS, with the exception of DIMP in well 37332. However, minor decreases or increases in these contaminants were noted in samples from several wells in this area. The contaminant distribution map for DIMP shows that the portion of the plume with the highest concentrations (i.e., greater than 10.0 μg/l) appears to be truncated at the NWBS. High historical DIMP concentrations were noted only in samples from well 37332, and decreases in DIMP concentrations were observed in samples from this well. Evaluations of the contaminant distribution map for dieldrin indicate that low levels of dieldrin persist downgradient of the NBS at the northeastern end and southeastern end and southwestern end of the hydraulic barrier. Both chloroform and fluoride concentrations near the NWBS remained relatively constant although detections of low concentrations of chloroform were more widespread and noted in samples from wells farther north than in the 1990 water monitoring year. Potentiometric data indicate that a gradient reversal was not achieved along the northeast extension of the slurry wall during the 1991 monitoring year. Based on this observation, the potential existed for flow through or underneath this portion of the NWBS. However, it is believed that contaminant migration is not occurring because of the slurry wall. Analytical results are inconclusive concerning the efficacy of this portion of the barrier wall.

5.3 BASIN F INTERIM RESPONSE ACTION AREA

Basin F, a lined evaporation basin that existed in Section 26 on RMA, was excavated as part of the Basin F IRA during 1988 and 1989. The Basin F IRA also provided for the construction of temporary containment structures to hold the contaminated liquid, soil, settled solids, liner, and overburden from Basin F. The Basin F IRA area consists of the following structures: a 92.7-acre surface depression formerly occupied by Basin F that has been excavated and covered with a contoured low-permeability clay cap; a 16-acre double-lined, enclosed waste pile within the historic perimeter of the basin; a double-lined collection pond adjacent to the waste pile for waste pile leachate; two double-lined liquid storage ponds immediately north of the basin; and three carbon steel holding tanks east of the basin. Water monitoring activities are performed in the Basin F IRA area to assess the effects of the Basin F IRA on groundwater flow and contaminant migration.

5.3.1 Groundwater Flow

Data from three CMP water-level measurement events were used in the evaluation of groundwater flow in the Basin F IRA area. The water-table surface in the Basin F IRA area is illustrated in Figures 5.2 through 5.4. A northwest-trending groundwater divide is evident in the west-central portion of Section 26. Northeast of the divide, groundwater flow is to the north and northeast. Southwest of the divide, groundwater flow is to the northwest.

Approximately two-thirds of the alluvium in Section 26 is unsaturated, and groundwater flow in the unconfined flow system occurs in the upper portion of the Denver Formation, as illustrated in Figure 5.2. In areas where the alluvium is unsaturated, the hydraulic gradient in the Denver Formation is generally steeper than in areas where the alluvium is saturated. This is believed to be caused by the lower hydraulic conductivity of the Denver Formation relative to the alluvium.

Of the three seasons when wells were monitored, water levels were the highest during Fall 1991. A small mound existed in the center of Section 26 during Fall 1991 when water levels were as much as 4 feet higher than during other seasons. Otherwise, water-level fluctuations were generally less than 1 foot between Spring 1991 and Fall 1991.

Water levels in the Basin F IRA area were similar from the 1990 to the 1991 water monitoring years except for northern portions of Section 26. Changes shown in the water table from the 1990 water monitoring year to the 1991 water monitoring year were mainly the result of changes in surveyed well reference points. The ground elevation was resurveyed and adjusted for some wells in the northern portions of Section 26, causing changes in the contour configurations. Potentiometric surfaces in the Basin F IRA area remained fairly constant from Fall 1989 to Winter 1990/91 for all Denver Formation zones (A, 1U, 1, 2, 3, and 4).

5.3.2 Contaminant Migration

Contaminant migration in the Basin F IRA area was assessed through the use of contaminant distribution maps and histograms. Sections 5.3.2.1 and 5.3.2.2 present discussions of contaminant migration in the unconfined and confined flow systems, respectively. Contaminant migration was assessed for DIMP, DBCP, dieldrin, chloroform, and fluoride.

5.3.2.1 Unconfined Flow System

Contaminant migration in the Basin F IRA area was assessed for the unconfined flow system through the use of histograms and Winter 1990/91 analytical data that were posted over the contaminant distribution plume maps of the unconfined flow system from Fall 1989.

The configurations of DIMP plumes in the unconfined flow system have not changed significantly in the Basin F IRA area since Fall 1989. Figure 4.13 illustrates the Fall 1989 DIMP plume with Winter 1990/91 detections posted. Winter 1990/91 detections are in close agreement with the observed Fall 1989 distribution, and no evidence of plume movement is readily apparent. Histograms of DIMP concentrations for wells near Basin F (Figure 5.51) show generally decreasing concentrations in samples from wells in the vicinity of Basin F since monitoring began in 1978.

The configuration of the DBCP plume extending northeast out of the northern Basin F IRA area in the unconfined flow system has not changed significantly since Fall 1989. Figure 4.12 illustrates the Fall 1989 DBCP plume with Winter 1990/91 detections posted. Histograms of DBCP concentrations for wells near Basin F (Figure 5.52) do not indicate any clear trends in DBCP concentrations in response to initiation of the Basin F IRA activities.

Figure 4.10 illustrates the Fall 1989 dieldrin plume with Winter 1990/91 detections posted. The configuration of the Fall 1989 dieldrin plume extending northeast out of the northern Basin F IRA area in the unconfined flow system is consistent with data collected during the 1990 water monitoring year. Histograms of dieldrin concentrations (Figure 5.53) indicate that dieldrin has been relatively static in the Basin F IRA area with slight increases or decreases in individual wells in no apparent areal pattern.

Figure 4.11 illustrates the Fall 1989 chloroform plume with Winter 1990/91 detections posted. Reported Winter 1990/91 chloroform concentrations decreased at wells 26133, 26157, 26148, and 23095 between Fall 1989 and Winter 1990/91. Winter 1990/91 increases in chloroform concentration occurred at wells 23241, 23179, and 23237 relative to Fall 1989 concentrations. Histograms of chloroform concentrations are presented in Figure 5.54.

Figure 4.14 illustrates the Fall 1989 fluoride plume with Winter 1990/91 detections posted. The fluoride plume extending northeast out of the northern Basin F IRA area in the unconfined flow system shows fluctuating values for some wells and similar values for other wells. Histograms of fluoride concentrations (Figure 5.55) show fluctuations in concentrations for all wells depicted. Fluoride concentrations increased or decreased at wells in an apparent random pattern in the Basin F IRA area.

5.3.2.2 Confined Flow System

Detections of contaminants in samples from the confined flow system in the Basin F IRA area are shown in Figures 4.15 through 4.19 for the 1991 water monitoring year. Relatively few wells monitor the confined flow system; therefore, analytical data are limited.

DIMP was reported in samples from four wells in the confined flow system in the Winter of 1990/91, two wells in the Denver Formation zone 1 and two wells in zone 2. All four detections were in samples from wells upgradient of Basin F. Levels of DIMP decreased in samples from wells 26066, 26129, and 26140 from Fall 1989 to Winter 1990/91. DIMP was reported in samples from well 26150 in Winter 1990/91; it was reported below the CRL for the same well in Fall 1989.

DBCP was reported in a sample from a well in the confined flow system in Winter 1990/91. The detection was for a Denver Formation zone 1 well (26140) upgradient of Basin F that was below the CRL in Fall 1989.

Low levels of dieldrin were reported in samples from two wells in the confined flow system in Winter 1990/91, one in the Denver Formation zone 1U and one in zone 2. Both wells are in Section 23, downgradient of the Basin F IRA area. Reported concentrations for these two wells remained relatively constant from Fall 1989 to Winter 1990/91. Dieldrin was reported in a sample from well 26084 in Fall 1989; detections in samples from this location were below the CRL in Winter 1990/91.

Chloroform was reported in samples from three wells in the confined flow system in Winter 1990/91. Chloroform levels decreased in samples from well 26140, upgradient of Basin F and in the Denver Formation zone 1. Chloroform was also detected in samples from two downgradient wells, 23189 (Denver Formation zone 3) and 23222 (Denver Formation zone 2), for which no detections were reported in Fall 1989. Chloroform was detected in samples from well 26129 in Fall 1989; detections in samples from this location were below the CRL in Winter 1990/91.

Elevated levels of fluoride (above 3000 μg/l) were detected in samples from seven wells in the confined flow system in Winter 1990/91: one in the Denver Formation zone 1, three in zone 2, two in zone 3, and one in zone 4. Four of these wells (26066, 26086, 26071, and 26129) are upgradient and three (26158, 23192, and 23193) are downgradient of the Basin F IRA area. Winter 1990/91 concentrations were generally higher than Fall 1989 values.

5.3.2.3 Summary

The existing analytical data are inconclusive regarding the effect of IRA remediation activities on groundwater contamination in the Basin F IRA area. In general, concentrations of DIMP and DBCP appear to be decreasing in the Basin F IRA area. The concentration of dieldrin appears to have remained relatively constant, and the concentration of chloroform appears to have remained constant or show occasional reductions in concentrations. Fluoride appears to fluctuate in a random pattern in the unconfined flow system throughout the Basin F IRA area and may have increased in concentration in the confined flow system from Fall 1989 to Winter 1990/91.

5.4 BASIN A NECK CONTAINMENT SYSTEM

The BANS IRA began operation in Spring 1990. MKE constructed the BANS to intercept and treat contaminated groundwater migrating from Basin A through the Basin A Neck paleochannel.

The BANS is composed of seven alluvial extraction wells in a northeast-southwest alignment across the Basin A Neck paleochannel perpendicular to the alluvial groundwater flow. Downgradient of the alluvial extraction well array is a soil-bentonite barrier wall that extends approximately 320 feet along a northeast-southwest alignment across the narrowest portion of the Basin A neck. The bottom of the barrier wall is keyed 2 feet into the Denver Formation bedrock to form a barrier to alluvial groundwater moving within the Basin A paleochannel. Groundwater treatment at the BANS consists of air stripping and using activated carbon to remove organic contaminants.

Three gravel-filled recharge trenches are located downgradient of the barrier wall and extend approximately 540 feet parallel to the barrier wall. Treated groundwater is recharged to the trenches in the unconfined flow system, with the goal of establishing a localized reverse gradient along the barrier wall.

The BANS was designed for a maximum flow rate of 32 gallons per minute (gpm) with average flows of 18 gpm. During the 1991 water monitoring year, average flow intercepted, treated, and recharged at the BANS was approximately 12 gpm. This amount compares closely to groundwater flow rates that were estimated for the Preliminary Engineering Design Package for the Basin A Neck Groundwater Intercept and Treatment System Interim Response Action (MKE, 1989). MKE estimated that flow through the Basin A Neck was 14 gpm. Additional groundwater contributions as a result of recirculation beneath the barrier wall were estimated at 7 gpm.

In addition to the groundwater flowing through the Basin A Neck, water from the IRA for the Groundwater Intercept and Treatment System North of Basin F at Rocky Mountain Arsenal was transferred to the Basin A Neck treatment facility. During the 1991 water monitoring year, groundwater extracted from North of Basin F was transferred by pipeline to the BANS.

The evaluation of groundwater flow in the area of the BANS was conducted through the use of water-table maps generated for each of the 1991 water monitoring year water-level monitoring events, as shown in Figures 5.2 to 5.4. Detailed assessment (cross sections and three-point gradient plots) of the hydrologic conditions at the BANS was not possible because of insufficient water-level data. The contour maps were constructed to evaluate the effects of the BANS on the local groundwater flow regime in this area. Figure 3.1 shows the locations of wells used for water-level measurements during the 1991 water monitoring year.

The unconfined flow system water-table elevation maps, Figures 5.2 to 5.4, show seasonal variations in water-table elevation to be relatively small. In the vicinity of the BANS, the 1991 water monitoring year water-table configuration is similar to the 1990 water monitoring year water-table configuration. This indicates the 1991 water monitoring year groundwater flow condition is similar to the groundwater flow condition of the previous years.

Because of the limited monitoring at the BANS, it was not possible to fully evaluate the effectiveness of the system in mitigating contaminant migration. An increase in the monitoring network and frequency is necessary to conduct a detailed evaluation of the BANS.

5.5 IRONDALE CONTAINMENT/TREATMENT SYSTEM

The ICS is a system of extraction wells, recharge wells, and a treatment system that forms a hydraulic barrier to offpost groundwater flow. It was designed to prevent the offsite migration of DBCP. The original system, completed in 1981, consisted of two rows of 33 dewatering wells and one row of 14 recharge wells. During the 1989/1990 period, the system was modified to include a total of 38 extraction wells and 22 recharge wells (MKE, 1992). The system is operated by Shell.

During 1990, Shell installed and sampled five new monitoring wells near the southern end of the ICS. The results of the sampling indicated that a small portion of the DBCP plume was bypassing the system in this area. During 1991, system modifications were completed to stop this bypass. An assessment of contaminant migration could not be conducted for the ICS because collection of CMP data for this area was limited to a regional, rather than a system-specific, focus during the 1991 water monitoring year. An assessment of the hydraulic impact of the ICS is provided below.

Because the areal density of wells for potentiometric data was not adequate to generate water-level cross sections or three-point plots, the evaluation of groundwater flow in the area of the ICS was conducted through the use of water-table maps only. All available water-level data from the 1991 water monitoring y were used in this evaluation, the locations of which are shown in Figure 5.37. The water-table maps were generated for each of the three monitoring events in 1991, as presented in Figures 5.2 through 5.4. These maps were constructed using a

2-foot contour interval to evaluate the effects of the ICS on the groundwater flow regime in this area.

During the Winter 1990/91 event, the water-table configuration was characterized by a mound centered around the recharge wells and an isolated low at the northeast end of the first row of extraction wells. The effect of the mound was to produce a reversal in hydraulic gradient (i.e., from northwest to southeast). The gradient to the southeast was approximately 0.02.

During the Spring 1991 event, a similar mound was evident, producing a gradient to the southeast ranging from approximately 0.02 to 0.03. One observed change was the development of a low in an area southwest of the ICS. This is probably a result of pumping from South Adams County Water and Sanitation District wells in this area. A gradient is evident from an area upgradient of the ICS toward this water-table low and also toward the northeast end of the ICS.

The water-table map for the Fall 1991 monitoring event shows a similar configuration to that observed for the Spring event, except that there was a more well-established cone of depression around extraction wells at the northeastern portion of the system.

Because of the limited monitoring at the ICS, it was not possible to fully evaluate the effectiveness of this system in mitigating offsite contaminant migration. However, Shell periodically prepares such assessments. An increase in the monitoring network and frequency would be necessary for the Army to conduct a detailed evaluation of the ICS.

6.0 GLOSSARY

>	greater than
<	less than
1,1,1-TCE	1,1,1-trichloroethane
AA	atomic absorption spectrometry
ALDRN	aldrin
Army	U.S. Department of the Army
AS	arsenic
BANS	Basin A Neck Groundwater Intercept and Treatment System
CF&I	Colorado Fuel and Iron Corporation
CFS	confined flow system
CH2CL2	methylene chloride
CHCL3	chloroform
CLC6H5	chlorobenzene
CLP	Contract Laboratory Program
CMP	Comprehensive Monitoring Program
COC	chain of custody
CPMS	p-chlorophenylmethyl sulfide
CQAP	Chemical Quality Assurance Plan
CR	chromium
CRL	certified reporting limit
CU	copper
CWP	Composite Well Program
DataChem	DataChem Laboratories
DBCP	dibromochloropropane
DCPD	dicyclopentadiene

DDT	dichlorodiphenyltrichloroethane
DIMP	diisopropylmethylphosphonate
DLDRN	dieldrin
DQO	data quality objectives
Ebasco	Ebasco Services, Inc.
ENDRN	endrin
EPA	Environmental Protection Agency
ESE	Environmental Science and Engineering, Inc.
F	fluoride
GB	isopropylmethyl fluorophosphonate
GC/FID	gas chromatography/flame ionization detector
GC/PID	gas chromatography/photoionization detector
GC/ECD	gas chromatography/electron capture detector
GC/MS	gas chromatography/mass spectrometry
GC/CON	gas chromatography/conductivity detector
GC/NPD	gas chromatography/nitrogen phosphorus detector
GC/FPD	gas chromatography/flame photometric detector
GMP	Groundwater Monitoring Program
gpm	gallons per minute
H	Levinstein mustard
HG	mercury
HLA	Harding Lawson Associates
HPLC	high performance liquid chromatography
Hyman	Julius Hyman and Company
ICP	inductively coupled argon plasma screen
ICS	Irondale Containment/Treatment System
ID	identification

IONCHROM	ion chromatography
IRA	interim response action
IRDMS	Installation Restoration Data Management System
ISP	Initial Screening Program
LSD	Laboratory Support Division
LT	less than Certified Reporting Limit
MIBK	methylisobutyl ketone
MKE	Morrison-Knudsen Engineers, Inc.
N/A	not applicable
NBS	North Boundary Containment/Treatment System
NS	not sampled
NWBS	Northwest Boundary Containment/Treatment System
PMRMA	Program Manager for Rocky Mountain Arsenal
PPDDT	2,2-bis(para-chlorophenyl)-1,1,1-trichloroethane
QA/QC	quality assurance and quality control
RI/FS	remedial investigation/feasibility study
RMA	Rocky Mountain Arsenal
RPD	relative percent difference
Sarin	isopropylmethyl fluorophosphonate
Shell	Shell Oil Company
Stollar	R.L. Stollar and Associates, Inc.
TCLEE	tetrachloroethene
TIC	tentatively identified compound
TOC	top of (well) casing
TOD	Technical Operations Division
UFS	unconfined flow system
USATHAMA	U.S. Army Toxic and Hazardous Materials Agency

USGS	U.S. Geological Survey
ZN	zinc
$\mu g/l$	micrograms per liter

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Appendix A

HYDROGEOLOGIC DATA COLLECTED DURING
THE 1991 WATER MONITORING YEAR

Appendix B

GAS CHROMATOGRAPHY DATA COLLECTED DURING
THE 1991 WATER MONITORING YEAR

Appendix C

GAS CHROMATOGRAPHY/MASS SPECTROMETRY DATA COLLECTED DURING
THE 1991 WATER MONITORING YEAR

PREFACE

Appendixes A, B, and C (on the enclosed diskette) present hydrogeologic data, gas chromatography data, and gas chromatography/mass spectrometry data, respectively.

To access a listing of the files on this diskette, type the following at the DOS prompt: DIR (space) (drive letter for diskette where list resides) :*.*.

For example: DIR A:*.*

To access the necessary files from this listing, retrieve the README.DOC file. This file explains how to access the other files. To view README.DOC, use any text editor or word processing software. You can also view README.DOC by typing the following at the DOS prompt: TYPE (space) (drive letter for diskette where README.DOC resides) :\README.DOC.

For example: TYPE A:\README.DOC

To print README.DOC, type the following at the DOS prompt: PRINT (space) (drive letter for diskette where README.DOC resides) :/README.DOC.

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